The viability of renewable energy and energy storage for the provision of power for desalination

Thesis

Link(s) to article on publisher's website:
http://dx.doi.org/doi:10.21954/ou.ro.0000eeb5

The viability of renewable energy and energy storage for the provision of power for desalination

Clifford Kwabena Nimakoh Dansoh

A thesis submitted in partial fulfilment of
the requirements of the Open University for
the degree of Doctor of Philosophy

September 2012

DATE OF SUBMISSION: 6 DECEMBER 2011
DATE OF AWARD: 17 NOVEMBER 2012

Acknowledgements

I am deeply indebted to Dr Ian Hill who has been unstinting in his encouragement and constructive criticism, well beyond the call of duty, and also to Dr. Suresh Nesaratnam for his support and technical guidance through the unfamiliar world of post graduate research.

The following have been especially helpful in the compiling of this thesis, and providing background information for it.

1. Andrew Ball of South East Water, for providing details of the typical water usage in the UK.
2. Andy Barton of CREST, for providing details of the efficiency of combining renewable energy power sources.
3. Daniel Shackleton of Salt Separation Services Limited, for giving so freely of his time to discuss reverse osmosis.
4. Dr Ameena P. Camps of Nottingham University, for her instruction in CCS and abiding with my inane rambling.
5. Dr Anotida Madzvamuse of Sussex University Mathematics Department, for his tireless assistance in developing the RO plant surface profile model.
6. Feddo Vollema of ARGOSS for the UK and Eritrea wave height information.
7. James Grinnell (formerly of Southern Water), for his time and candour in discussion of municipal water supplies.
8. Lisa Freeman and Mike Gabriel of Power Electrics (Bristol) Limited, for the diesel generator price details.
9. Martin Hind of Biwater, for the desalination information provided.
10. Dr. Murray Thomson of CREST, for the Eritrea seawater temperature information.
11. Nicola Ramsden of Desal Supplies Limited, for details of the reverse osmosis membrane prices.
12. Paul Wilson of Parsons Brinkerhoff for his time and effort in relation to the prices of renewable and conventional power.
13. Philip Boswell of Accepta, for the information provided on reverse osmosis chemical costs.
14. Rupert Gannon of CREST, for his time in awful weather conditions at West Beacon Farm, and the benefit of his expertise on all aspects of renewable energy.
15. William Conlon and Ismael Diaz of Parsons Brinkerhoff for their time and enthusiasm for the

many aspects of reverse osmosis desalination that I called upon them for.

Finally, I would like to dedicate this thesis to my wife Mary, in grateful thanks for her patience, support and continued enthusiasm throughout the long project.

Table of contents

Table of Figures

Table of Tables

Abbreviations

The following abbreviations are used within this thesis.

Abbreviation	Definition
AA	Automobile Association
AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
A/cm^2	Amps per square centimetre
AC	Alternating Current
AM	Air Mass Coefficient
ARC	Anti-Reflective Coating
BAP	Biodiversity Action Plan
BAU	Business As Usual
BBC	British Broadcasting Corporation
BSR	Brine Stream Recovery
BWEA	British Wind Energy Association
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CEO	Chief Executive Officer
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
CoP	Coefficient of Performance
CoFP	Coefficient of Financial Performance
CSP	Concentrated Solar Power
CTA	The International Centre for Technology Assessment
DAC	Direct Air Capture
DC	Direct Current
DCF	Discounted Cash Flow
DTI	Department of Trade and Industry
ECF	European Climate Foundation
EDLC	Electric Double Layer Capacitor
EPRI	Electric Power Research Institute Incorporated
EREC	European Renewable Energy Council
EU	European Union
EU SETIS	European Union Strategic Energy Technologies Information System
ExternE	Externalities of Energy, A research project of the European Commission
FAO	Food and Agriculture Organisation
FCTec	Fuel Cell Test and Evaluation Centre
FiT	Feed in Tariff
GDP	Gross Domestic Product
GEAS	Global Environmental Alert Service
GENI	Global Energy Network Institute
GTZ	Gesellschaft für Technische Zusammenarbeit (German Technical Cooperation)
GW	Giga Watts
GWh/year	Giga Watt hours per year
H_2	Hydrogen

Abbreviation	Definition
HFC	Hydro Fluorocarbon
HOMER	Energy Modelling Software for Hybrid Renewable Energy Systems
HP P/p	High Pressure Pump
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IWA	International Water Association
MED	Multi-Effect Distillation
MGD	Millions of Gallons per Day
MSF	Multi-Stage Flash Distillation
MW	Mega Watts
MWh	Mega Watt hours
NASA	National Aeronautics and Space Administration
NEEDS	New Energy Externalities Developments for Sustainability
NO_2	Nitrogen Dioxide
NOABL	The Department of Trade and Industry wind speed database
NPV	Net Present Value
NPW	Net Present Worth
O_3	Ozone
OECD	Organisation for Economic Cooperation and Development.
OPEC	Organisation of Petroleum Exporting Countries
PEM	Proton Exchange Membrane
PFC	Per Fluorocarbons
PM	Particulate Matter
POST	Parliamentary Office of Science and Technology
ppm	parts per million
PRODES	Promotion of Renewable Energy for Water production through Desalination
PV	Photovoltaic
PW	Pelton Wheel
PX	Pressure Exchanger
R	Correlation Coefficient
R^2	Coefficient of Determination
R&D	Research and Development
REDDES	Commission of the European Communities Directorate-General for Energy and Transport ALTENER Programme – Renewable Energy Driven Desalination Systems
REN21	Renewable Energy Networks for the 21^{st} Century
RO	Reverse Osmosis
ROC	Renewable Obligation Certificate
SEEDA	South East England Development Agency
SMES	Super Conducting Magnetic Energy Storage
SNCI	Site of Nature Conservation Importance
SO_2	Sulphur Dioxide
SSSI	Site of Special Scientific Interest
STC	Standard Test Conditions
SWRO	Seawater Reverse Osmosis
TDS	Total Dissolved Solids
UK	United Kingdom

Abbreviation	Definition
ULCDS	Ultra–Low Carbon Dioxide Steelmaking
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UNESCO	United Nations Educational, Scientific and Cultural Organisation.
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nation's Children's Fund
UNIDO	United Nations Industrial Development Organisation.
UPHS	Underground Pumped Hydro Storage
USA	United States of America
UV	Ultra Violet
VA	Volt-amperes or apparent power
VSL	Value of Statistical Life Lost
WHO	World Health Organisation
WBCSD	World Business Council for Sustainable Development
WWF	World Wildlife Foundation

Nomenclature

Abbreviation	Definition
δ	(delta). Rate of pure time preference
η	(eta), determines how strongly economic growth affects the discount rate. A larger value of η implies a larger discount rate, and hence less need to provide today for future generations (as long as per capita consumption is growing).
µm	Micrometre
Ad_{wat}	Percentage of additional water produced by using hydrogen fuel
A/cm^2	Amps per square centimetre
CoP	Coefficient of Performance
$Cost_{hf}$	The cost of hydrogen conversion and storage equipment, and fuel cells to achieve $Cost_{sav}$
$Cost_{sav}$	The reduction in cost of scaled-up RO plant and power installed due to use of hydrogen fuel
En_{was}	Percentage of energy produced by the plant that was wasted.
g	Growth rate of per capita consumption. If per capita consumption is constant, implying that $g = 0$, then the discount rate $r = \delta$.
GW	Giga Watts
GWh/y	Giga Watt hours per year
H_s	Significant wave height
i	The discount rate (the return that could be earned on an investment in the financial markets with similar risk.); the opportunity cost of capital.
k	Weilbull shape factor
K	Kelvin
km	kilometre
km^2	Square kilometre
km^3	Cubic kilometre
kVA	Kilo Volt Amps
kW/A	Kilowatt per Annum
kW_{el}	Kilowatt electrical power
kWh	Kilo Watt hour
kWh/m^3	Kilo Watt hour per cubic metre of water produced
kW_{H2}	Kilowatt hydrogen power
kW/m	kilowatts per metre
m^3/day	cubic metres per day
m^3/h/day	cubic metres per hour per day
mm	millimetre
m/s	Metres per second
R^2	Coefficient of determination
Rt	The net cash flow (the amount of cash, inflow (value of water sold) minus outflow (the cost to maintain the power source and RO plant) at time t
t	The time of the cash flow.
TW	Terra Watts
TWh	Terra Watt hours
TWh/y	Terra Watt hours per year
W/m^2	Watt per metre
W/m^2/day	Watts per square metre per day

Abstract

This research investigates the viability of renewable energy and energy storage to meet a significant and fundamental human need (in this case, large-scale drinking water supplies) unassisted by conventional power.

The use of renewable energy to power reverse osmosis desalination plants to provide potable water for around 50,000 people in Newhaven, in South East England, and in Massawa in Eritrea, was investigated.

The following energy sources, in a variety of combinations were specifically assessed:

- Wind Power
- Wave Power
- Solar Power
- Tidal Current Power
- Hydrogen production, storage and use in Fuel Cells

The following types of reverse osmosis plants were studied:

- No Brine Stream Recovery (BSR) reverse osmosis plant
- Pelton Wheel BSR reverse osmosis plant
- Pressure Exchanger BSR reverse osmosis plant

Modelling was conducted to derive the amount of water that each reverse osmosis plant would deliver from various combinations and amounts of renewable power input, at varying feedwater temperatures. Scenarios that were not able to deliver enough water to meet the users' needs were scaled-up so that they could.

The cost of the scaled-up scenarios that were able to meet the users' water demands were compared with the costs associated with the equivalent conventionally-powered scenario over a 25-year life. Specifically, the following were considered:

- A coal-fired plant with carbon capture and storage (CCS) at Newhaven and
- A diesel generator at Massawa.

This comparison was made with and without the external costs associated with conventional energy production and use.

The most financially-attractive scenario at each site was then assessed for its ability to meet the daily demand for water, over the course of a year.

A comparison of the most financially-attractive renewable energy option and the equivalent conventionally-powered scenario at Massawa was undertaken, based on Net Present Value (NPV) methodology.

1 Background

One of the major problems with the use of renewable sources of energy is their tendency to vary (sometimes referred to as 'intermittency'). This frequently means that they are unable to service a demanded load with confidence due to unavoidable natural fluctuations. Renewable energy is therefore currently considered to only have viability for a small portion of energy delivery within a larger system and is generally restricted to supplying major grid networks.

This intermittency potentially undermines the energy security advantages on offer from decentralisation of supply.

The purpose of this research is to investigate the use of renewable energy sources in such a way that they could be justified for use without reliance on conventional energy sources and to stand alone as an independent and viable power source in their own right. This was investigated by modelling the use of renewable energy for a fundamental human use on a significant scale, as a thought experiment, to see if it was possible to use renewable electricity derived from local energy sources where conventional electricity would normally be employed.

1.1 Energy

As the world population of seven billion people strives for a standard of living that is taken for granted in the developed world, energy demand will increase, thereby straining the entire supply chain from exploration to refining.

1.1.1 Humans and energy use

Originally humankind supplemented human muscle power with energy from other sources, such as draft animals. Now, technology based on external energy inputs such as the internal combustion engine provides humans with the means to support a population density that is far in excess of other species. Technology (and energy at its base) ultimately defines the carrying capacity of the Earth for humans, and today's population far exceeds that which could be maintained by traditional means (estimated at around 3 billion [Mearns, 2007]).

In terms of primary energy consumption, the average American consumes roughly 100 times their metabolic power input[1], and maintenance of such an elevated carrying capacity requires continued access to readily available energy. The global energy consumed in 2010 was around 150000TWh [Enerdata, 2011] and the trend over the last 20 years has been an increase of almost 50%.

This presents potential problems if the continued (and increasing) access to readily available power is based upon conventional supplies. These conventional supplies:

- Have the potential to run out (and therefore not meet the expected user demand)
- Have a direct impact on our health and this impact has the potential to increase with more widespread use
- Are a contributory factor to climate change.

The following sections will look into the potential for conventional energy to continue to supply the increased energy demand and maintain our elevated population densities.

With regard to the potential difficulties with the continued supply of conventional energy, oil is taken as the example for analysis.

1.1.2 The oil peak

The main argument that conventional energy supplies will fail to continue to meet demand is based around Hubbert's peak.

Hubbert describes a peak oil hypothesis, and indicates that the limitations in oil supply will make themselves felt long before all the oil has been consumed. It assumes a logistic curve for the extraction of oil, and suggests that maximum production will be reached when half of all the oil is consumed[2].

How close we are to the oil peak is a point of much debate. A thorough debate on the existence, timing and significance of an impending 'peak' of global oil production[3], was held in 2004.

The first presentation was by Chris Skrebowski[4] who noted that the quality of the available data was the reason that interpretations of the situation were both variable and ambiguous, and it was considered that

---

[1] With a population density about 100 times larger than the expected "natural" level, and energy consumption 100 times larger than the metabolic level, Europeans and Americans enter the ecological system with power consumption per unit area which exceeds that of other species by about four orders of magnitude.

[2] Based on this logic, K. Hubbert in 1956 predicted correctly the peak in the oil production in the continental United States which occurred in 1970.

[3] This debate was conducted at the Energy Institute in London on 10 November 2004. It was reported by Petroleum Review in the January 2005 edition of the Energy Institute publication 'Energy World' under the title 'Oil depletion – crisis, concern or no problem?'

[4] Editor of the Energy Institutes Petroleum Review.

this enabled some to conclude that there was concern or crisis, and others were able to conclude that there was no problem[5].

Dr Roger Bentley[6] was the second speaker on the subject of data discrepancies, and noted that the way that data was interpreted fell into two distinct categories:

- Geologists generally saw peak oil as being relatively close, while
- Economists either considered it some way into the future, or denied the possibility of it occurring[7].

Dr Bentley considered that there were four key unresolved issues:

- The real size of reserves
- The size and significance of discovery growth
- The size and significance of reserves growth, and
- The speed of development of non-conventional oil and oil substitutes.

He contrasted the enormous size of the unrecovered oil in place, with the latest production forecasts which indicate peak oil and liquids production around 2012. This was supported by (mainly geologists) estimates of peak production between 2005 and 2025, but was countered by mainly economists' estimates which either did not indicate a peak or (where they did) one that occurred after 2030. He noted that the economists justified their estimates by stating that other estimates failed to credit human ingenuity, and that higher prices increased supply and decreased demand, and that there was a large technology gain.

Dr Bentley concluded his presentation with his own peak estimates:

Non-OPEC conventional oil	now
Global conventional oil peak	2010 – 2015
Global all oil	2015 – 2020
Global oil and gas	2015 – 2020
Global gas	2020 - 2025

Francis Harper of BP, gave the geologist's view and his overall conclusions that:

- Existing discovered reserves are unlikely to sustain the world's population for more than about 15 years

---

[5] Richard Pike, a former oil industry Advisor and Chief Executive of the Royal Society of Chemistry (reported in the New Scientist. 11 June 2008) blamed flawed statistical calculations, which he claimed were potentially significantly underestimating the available reserves.

[6] From the University of Reading who gave a presentation entitled: 'Global oil depletion: viewpoints in collision'.

[7]Dr Bentley considered that the main reason for this was the quality of the reserves data, and the discrepancies between the industry data often accessible by the geologists, and the public data more commonly used by the economists.

- Exploration cannot be expected to replace production, and its contribution may continue to decline
- Reserves growth is likely to continue as the dominant form of reserve additions, but much of it will only slow the post-peak production decline
- Non-conventional oil will become increasingly important – there is a very large resource, but converting it into reserves has significant financial and environmental cost, and
- The non – OPEC contribution is likely to reach a resource constrained peak from conventional oil in the next 10 years – thereafter, production capacity will be concentrated in progressively fewer countries.

Professor Peter Odell was the fourth speaker, and presented the economist's view[8].

He noted that the issue of future oil supply has been a recurring theme, as encapsulated in the pamphlet: 'Oil Crisis...Again?' [BP,1979], which foresaw oil production outside the Soviet Bloc peaking in 1985[9], and then explained that such analysis failed because of:

- *The rigidity of the assumptions about discovery, and;*
- *The 'absurd' notion that oil had a perfect elastic supply price curve'.*

He then went on to explain that (as far as he was concerned) using the publicly available reserves databases, discovery had exceeded consumption meaning as he put it that:

> *'the world was running into oil' rather 'than running out of it'.*

Although only oil was discussed above, all conventional fuels (including coal, oil shale, tar sands, etc) are finite. Though there are enough of these conventional fuels to last for a considerable time, although this is also questioned within 'The great coal hole' [Strahan, 2008], it will become more difficult and/ or expensive to extract and process them for energy production as explained in 'scrapping the bottom of the barrel' [Strahan, 2009]. Even then, the IEA Chief Economist, Faith Birol says that:

> *'...non conventional fuels [oil shales and tar sands] will probably only defer peak oil to 'around 2030'.*

1.2 Environmental and health impacts of energy use

The greater constraint on the continued use of conventional fossil fuel is likely to come from environmental concerns, especially:

---

[8] Professor Odell gave a presentation entitled 'Oil's long term future – 85% yet to be exploited'.

[9] This forecast is examined by Dr. Roger Bentley (who was the second speaker at this event) at his 'Past Oil Forecasts' webpage http://www.oildepletion.org/roger/Key_topics/Past_forecasts/past_forecasts1.htm [Last viewed on 7 August 2011]. Making adjustments to the report's findings to account for assumptions about the fuel types and sources, and oil production aligning with demand gives a more reasonable forecast of a fall in global conventional oil production from around the year 2000.

- The direct effects of conventional energy use on human health, and
- The rising concentration of atmospheric CO_2, a greenhouse gas.

The main outputs of conventional fossil fuel combustion are shown below in Table 1.

Table 1: Health impacts of fossil fuel combustion

	Detail
Carbon dioxide	Carbon dioxide is the principle product of the combustion of hydrocarbon fuels. It is a colourless and essentially odourless gas that is one and a half times as dense as air. It is not particularly toxic, although a large concentration could result in suffocation simply by causing a lack of oxygen in the body. The effects of carbon dioxide in the atmosphere are controversial. However, the average temperature of the Earth is rising, especially when measured at the Poles, and it is noteworthy that the average Earth surface temperature correlates well with the amount of CO_2 in the atmosphere (i.e. as the CO_2 levels in the atmosphere have increased, the surface temperature has gone up). Also, half of the extra CO_2 from the atmosphere will dissolve in the oceans, making the water more acidic, which will have an impact on marine life.
Carbon monoxide	All fossil fuel combustion systems emit some carbon monoxide, but it is generally associated with sub-stoichiometric combustion. Its significance is related to its highly toxic nature. It is colourless and odourless, and gives no sensory warning of its presence. It binds to the haemoglobin in blood, and in that situation the haemoglobin cannot combine with oxygen. A concentration of less than one percent in inspired air seriously impairs oxygen binding capacity, and if exposed to this level for a sustained period, death will ensue. Carbon monoxide has an indirect effect on the 'Greenhouse Effect' by depleting atmospheric levels of hydroxyl radicals and slowing the destruction of methane, which is a powerful 'Greenhouse Gas' in its own right.
Oxides of nitrogen	Oxides of nitrogen are produced during high-temperature combustion. The emission of nitrogen oxides to the atmosphere has led to the acidification of rain and aquatic systems.
Oxides of sulphur	Coal burning is the single largest anthropological source of sulphur dioxide, accounting for about 50% of annual global emissions, with oil burning accounting for a further 25-30%. Sulphur dioxide (SO_2) is a colourless, non-flammable gas with a penetrating odour that irritates the eyes and air passages[10].
Ozone	Ozone is a naturally occurring gas that is found in two layers of the atmosphere. In the layer surrounding the Earth's surface (the troposphere) ground-level or "bad" ozone is an air pollutant that is a key ingredient of urban smog. The troposphere extends up to the stratosphere, where "good" ozone protects life on Earth by absorbing some of the sun's UV rays. Stratospheric ozone is most concentrated between 10 to 50 Km above the Earth's surface.
Particulates	Coarse particulates are classified as those with a diameter greater than 2.5 micrometres (μm), and fine particles are those with a diameter less than 2.5 micrometres. A further distinction that can be made, is to classify particulates as either primary or secondary, according to their origin[11]. Particulate matter is emitted from a wide range of anthropological sources, including industrial combustion plants and processes and can have significant health impacts[12].

Exposure to ambient air pollution caused in part by use of conventional fossil fuels, has been linked to a number of different health problems [WHO, 2004] ranging from modest transient changes in the respiratory tract and impaired pulmonary function, continuing to restricted activity/reduced performance,

---

[10] The health effects of sulphur dioxide pollution were exposed graphically during the "Great Smog" of London in 1952. This resulted in approximately 4000 premature deaths through heart disease and bronchitis. Since then, however, emissions have been significantly reduced through legislative controls and the introduction of clean fuel technology. Research has shown that exposure for asthmatics is significantly more damaging than for normal subjects, and sulphur dioxide pollution is considerably more harmful when particulate and other pollution concentrations are high. This is known as the "cocktail effect."

[11] Primary particulates are those emitted directly to the atmosphere, while secondary particulates are those formed by reactions involving other pollutants. In the urban environment, most secondary particulate matter occurs as sulphates and nitrates formed in reactions involving sulphur dioxide and nitrogen oxides.

[12] Particulates may be seen as the most critical of all pollutants, and some estimates have suggested that particulates are responsible for up to 10,000 premature deaths in the UK each year. Fine particles of less than 10 micrometres (μm) in diameter can penetrate deep into the lung and cause more damage, as opposed to larger particles that may be filtered out through the airways' natural mechanisms.

emergency room visits and hospital admissions, and to mortality. There is also increasing evidence for adverse effects of air pollution not only on the respiratory system, but also on the cardiovascular system. The results from a World Health Organisation (WHO) Review strongly suggest that a reduction in air pollution will lead to health benefits[13].

The WHO Review also considered whether no effect thresholds[14] exist for the main pollutants of Particulates, Ozone and NO_2. Based on recent scientific studies, it was unable to identify such thresholds and was not able to confirm that the current limitations were adequate to guarantee no adverse health effects.

Carbon dioxide (and specifically the carbon dioxide emitted by the combustion of conventional fossil fuels[15]) is attributed to playing a significant part in the greenhouse effect[16] and causing climate change. The actual physical impacts and consequences of climate change are controversial and difficult to judge with any accuracy, but Table 2 below (taken from the Intergovernmental Panel on Climate Change [IPCC, 2007] report on climate change impacts) provides an overview of the potential impacts.

---

[13] The WHO states that their conclusion regarding the benefit of reductions in air pollution is also in line with recent "intervention studies" that have demonstrated health benefits following the reduction of pollution levels under various circumstances.

[14] This implies no effects of increasing air pollution until a "threshold" concentration is surpassed, at which stage risk rises.

[15] Fossil fuels at present provide 85% of the commercial energy that is consumed world wide, and for every ton of carbon consumed, 3.7 tons of carbon dioxide are emitted to the atmosphere.

[16] The critics point out that the dynamics of the water cycle in the atmosphere is very complex, and that it is not very well captured by the current generations of models. The overall effect one is looking for is quite small and it depends on fine details in the water distribution between clouds, and water vapour, between the upper and the lower troposphere. Changes in these parameters could, in principle, also explain the lower-than-expected rise in temperature, in which case the global warming may not be as large as has been suggested.

Table 2: Predicted physical impacts of Climate Change

Phenomenon and direction of trend	Likelihood of future trends based on projections for 21st century	Examples of major projected impacts by sector			
		Agriculture, forestry and ecosystems	Water resources	Human health	Industry and society
Over most land areas, warmer and fewer cold nights, warmer and more frequent hot days and nights.	Virtually certain	Increased yields in colder environments. Decreased yields in warmer environments. Increased insect outbreaks.	Effects on water resources relying on snow melt. Effects on some water supplies.	Reduced human mortality from decreased cold exposure.	Reduced energy demand for heating. Increased energy demand for cooling. Declining air quality in cities. Reduced disruption to transport due to snow and ice. Effects on winter tourism.
Warm spells and heat waves. Frequency increases over most land areas.	Very likely	Reduced yields in warmer regions due to heat stress. Increased danger of wildfire.	Increased water demand. Water quality problems, e.g. algal blooms.	Increased risk of heat related mortality, especially for the elderly, chronically sick, very young and socially isolated.	Reduction in quality of life for people in warm areas without appropriate housing. Impacts on the elderly, very young and poor.
Heavy precipitation events.	Very likely	Damage to crops. Soil erosion. Inability to cultivate land due to waterlogging of soils.	Adverse effects on quality of surface and groundwater. Contamination of water supply. Water scarcity may be relieved.	Increased risk of deaths, injuries and infectious, respiratory and skin diseases.	Disruption to settlements, commerce, transport and societies due to flooding. Pressures on urban and rural infrastructure. Loss of property.
Area affected by drought increases.	Likely	Land degradation. Lower yields/ crop damage and failure. Increased livestock deaths. Increased risk of wildfire.	More widespread water stress.	Increased risk of food and water shortage, malnutrition, water and food borne diseases.	Water shortages for settlements, industry and societies. Reduced hydropower generation potentials. Potential for population migration.
Intense tropical cyclone activity increases.	Likely	Damage to crops. Windthrow (uprooting) of trees. Damage to coral reefs.	Power outages causing disruption to public water supply.	Increased risk of deaths, injuries, water and food borne diseases, post traumatic stress disorders.	Disruption by flood and high winds. Withdrawal of risk coverage in vulnerable areas by private insurers. Potential for population migration. Loss of property.
Increased incidence of extreme high sea level. This excludes tsunamis.	Likely	Salination of irrigation water, estuaries and freshwater systems.	Decreasing freshwater availability due to saltwater intrusion.	Increased risk of deaths and injuries by drowning in floods. Migration related health effects.	Costs of coastal protection vs. costs of land-use relocation. Potential for movement of populations and infrastructure.

The impacts reported in the table are entirely qualitative, but there are some more specific estimates [nowpublic.com].

For example, Wong Poh Poh, a Professor at the National University of Singapore, told a regional conference that global warming was disrupting water flow patterns and increasing the severity of floods, droughts and storms — all of which reduce the availability of drinking water.

Professor Wong said:

> *'.. .the U.N. Intergovernmental Panel on Climate Change found that as many as 2 billion people won't have sufficient access to clean water by 2050. That figure is expected to rise to 3.2 billion by 2080 — nearly tripling the number who now do without it.'*

Although there are many possible negative outcomes, it is important to also appreciate the potential positive aspects. A slight warming may:

- Make some locations more habitable, and

- Improve our ability to feed ourselves[17].

There is a range of levels of stabilisation of carbon dioxide in the atmosphere being considered, based on the perceived consequences of a continued accumulation of carbon dioxide in the atmosphere. One option would be to aim for 550ppm. Others who have confidence in the IPCC predictions may want to set the level at 450ppm. Those who are sceptical about the details of the models, and who may have a rather high tolerance for ecological change may settle for 650 or even 750ppm.

Whatever the number, the fact is that uncontrolled growth of fossil fuel energy usage has to be slowed. The option to do nothing is apparently no longer viable according to the Stern Report.

1.2.1 Stern Report

The Stern Report [Stern, 2007] discussed the effect of global warming on the world economy and its conclusions were that action on climate change is required now[18]. This has caused much debate amongst economists, which is concisely collated in 'Debating Climate Economics: The Stern Review vs. Its Critics' [Ackerman' 2007].

A précis of the Report's main conclusions is listed below:

- The benefits of strong, early action on climate change outweigh the costs.
- The scientific evidence points to increasing risks of serious, irreversible impacts from climate change associated with business-as-usual (BAU) paths for emissions.
- Climate change threatens the basic elements of life for people around the world — access to water, food production, health, and use of land and the environment.
- The impacts of climate change are not evenly distributed — the poorest countries and people will suffer earliest and most.
- If and when the damages appear, it will be too late to reverse the process. Thus we are forced to look a long way ahead.
- Climate change may initially have small positive effects for a few developed countries, but it is likely to be very damaging for the much higher temperature increases expected by mid-to-late century under BAU scenarios.

---

[17] In the case of agriculture where a good case could be made that net total changes are positive, there will be winners and losers. It may well turn out that plenty of land in Canada and Siberia will become accessible to modern agriculture and thus lower the cost of food, while at the same time a smaller amount of land in warm zones of the globe becomes either too hot, too dry or too variable in rainfall to continue to support agriculture.

[18] Although not the first economic report on climate change, it is significant as the largest and most widely known and discussed Report of its kind to date.

- Integrated assessment modelling provides a tool for estimating the total impact on the economy, and this is likely to be higher than previously suggested.
- Emissions have been, and continue to be, driven by economic growth; yet stabilisation of greenhouse gas concentration in the atmosphere is feasible and consistent with continued growth.
- Central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2e (i.e. equivalent CO_2) are around 1% of global GDP, if we start to take strong action now. It would be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may 'slip away.'
- The transition to a low-carbon economy will bring challenges for competitiveness but also opportunities for growth. Policies to support the development of a range of low-carbon and high-efficiency technologies are required urgently.
- Adaptation policy is crucial for dealing with the unavoidable impacts of climate change, but it has been under-emphasised in many countries.
- There is still time to avoid the worst impacts of climate change if strong collective action starts now.

It is clear that the option to 'do nothing' regarding climate change is widely acknowledged as being unacceptable.

This, when combined with:

- The envisaged scarcity of conventional fossil fuels and the adoption of potentially costly alternatives.
- The health impacts associated with air pollution and the significant benefits to be achieved by a reduction in air pollution, means that it is doubtful that conventional energy will be viable to support any increased energy need for a significant period.

It is concluded that continued reliance on fossil fuels does not seem a reasonable option, but there will still be an increasing need for energy.

To meet this ongoing need for energy, it is proposed that renewable energy is employed in place of convention fossil fuels.

There are of course other options to mitigate the impact of climate change such as extracting CO_2 and other greenhouse gases from the atmosphere to reduce the current CO_2 loading.

The direct air capture (DAC) of CO_2 from the air generally involves funnelling airflows over a chemical sorbent that selectively removes the CO_2. The CO_2 is then released as a concentrated stream for disposal or reuse, while the sorbent is regenerated and the CO_2-depleted air is returned to the atmosphere. The viability of this process is discussed at length at Direct Air Capture of CO_2 with Chemicals [APS, 2011] which having conducted a lengthy investigation concluded that, although there was future merit, the technology is not currently an economically viable approach to mitigating climate change.

1.3 Using renewable energy in place of conventional fuels

There are several scenarios being presented how 100% reliability on renewable energy may be achieved. The following sections present an overview of these scenarios for:

- Britain
- Europe, and
- The world as a whole.

1.3.1 The UK

The Centre for Alternative Technology in Wales has published 'Zero Carbon Britain' [CAT, 2010], a comprehensive report which indicates all the changes that must be made to achieve zero carbon in Britain, by 2030.

A précis of the changes required to achieve this scenario is given below, in Table 3. It is noteworthy that there is a heavy reliance on carbon sequestration.

Table 3: Changes required to achieve zero carbon in Britain

Source	Volume of CO_2 (Millions of tonne)	Percentage of total 'greenhouse gas' UK emissions (%)	The zerocarbonbritain 2030 scenario.
Industrial and commercial combustion	83	13	That these processes are supplied with electricity, hydrogen, heat pumps and biomass Combined Heat & Power (CHP)
Landfill	19.5	3	It is estimated that through a mixture of improved landfill gas recovery, improved capping of landfill, and a reduction in biodegradable waste sent to landfill, emissions from landfill in the UK could be reduced to 177,000 tonnes CH_4, or 4.4 million tonnes of CO_{2e} by 2020. Converting this UK figure to one for Great Britain gives 4.2 million tonnes of CO_{2e}.
The "super greenhouse gases": HFCs, PFCs and SF6		1.5	Assumes that by 2030 emissions from the super greenhouse gases will have been reduced to 10% of their current quantity.
Cement production	5.7	1	Assumes reduction due to the shift to more ecological building techniques, which actually sequester carbon. In the case of cement, this can also be reduced through combining it with pulverised fuel ash. It is therefore assumed that emissions from cement production will fall by 90%.
Adipic and nitric acid production	2.8	0.5	By changing production processes, it is possible to reduce emissions from the production of these acids by 90–98% at a low cost of less than 5 dollars a tonne of CO_2e. It is therefore assumed that emissions are reduced by 97%.
Lime Production	1	0.1	Lime production and its associated emissions are trebled, due to the increased growing of biomass for energy production and carbon sequestration.
Iron and steel production			It is possible to produce iron ore using either hydrogen or electrolysis instead of carbon and the processes have been demonstrated at a small scale (Ultra–Low Carbon Dioxide Steelmaking [ULCOS, 2010][19]. Assuming the electricity is renewably produced, producing steel using electrolysis should be able to reduce greenhouse gas emissions to close to zero, but the reduction of iron ore by these methods is considered to be decades away from commercialisation. For this reason it has not been included in the scenario, but it is useful to note that in the longer term it should be possible to almost entirely decarbonise iron and steel production.
Other industrial processes e.g. glass and chemical manufacturing.	1	0.1	These remain unchanged in the scenario although it may be possible to reduce some or all of them. Further work would be necessary to establish where reductions could be made.
Land use change: land converted to settlements	5.7	0.9	That town planning is adapted with the aim of increasing the density of existing settlements rather than encouraging continued outward urban sprawl. For this reason it is assumed that emissions from land conversion to settlements are reduced by 30% in the 2030 scenario, to 4 million tonnes.
Remainder of emissions	67	Probably over 80%	Will need to be matched by sequestration.

1.3.2 Europe

Roadmap 2050: a practical guide to a prosperous, low-carbon *Europe* [ECF, 2011] concludes that Europe could move to low carbon sources of electricity, with up to 100% coming from renewables by 2050, without:

- Risking energy reliability, or
- Raising energy bills.

[19] Details of the electrolysis process employed to produce steel are available at the Ultra–Low Carbon dioxide (CO_2) Steelmaking (ULCOS) 'Alkaline Electrolysis' web page available at http://www.ulcos.org/en/research/electrolysis.php [Last viewed on 7 August 2011].

To account for increased demand, it looked at scenarios supplying 40% more electricity than at present by 2050, with various mixes of renewables, from 40% up to 100%[20], all of which are claimed to be technically viable.

However, the Report notes that the transition to zero carbon power is heavily reliant upon European Union (EU) member states prioritising energy efficiency measures, and supporting the rapid development of a European electricity 'supergrid', to help distribute and balance the green energy, and manage demand.

For the 40–80% renewable scenarios, there would also be a need for 190 to 270 GW of back-up generation capacity to maintain the reliability of the electricity system, but the European Climate Foundation (ECF) notes that 120 GW of that already exists. For new back-up, it looks to more gas-fired plants, biomass/biogas fired plants, and hydrogen-fuelled plants, potentially in combination with hydrogen production for fuel cells.

For the 100% renewables scenario:

- 15% of the energy would be imported via a 'supergrid' link from Concentrating Solar Power (CSP) plants in North Africa, and
- 5% would be derived from enhanced geothermal sources around the EU.

'100% renewable electricity - A roadmap to 2050 for Europe and North Africa' [PwC, 2010] is also of the view that Europe and North Africa could be powered exclusively by renewable electricity by 2050, but relies on a single European power market, linked with a similar market in North Africa.

As is the case with Roadmap 2050, the use of a Super Smart Grid is proposed to allow for load and demand management, and to integrate the renewable energy. The 100% scenario calls for:

- Concentrating Solar Power Plants in the deserts of North Africa, and also in southern Europe.
- The hydropower capability of Scandinavia and the European Alps.
- Onshore wind farms and offshore wind farms in the Baltic and North Sea, and
- Tidal and wave power and biomass generation across Europe.

This study concludes that:

- '*The most recent economic models show that the short term cost of transforming the power system may not be as large as previously thought.*'
- Overall reliability would not be compromised.

[20] It is noteworthy that carbon capture and storage (CCS) and nuclear are not included in the 100% renewable scenario.

- The development of North African resources '*could pay big dividends in terms of regional development, sustainability and security.*'

The European Renewable Energy Council [EREC, 2010] claims that the EU could not only meet up to 100% of its electricity demand from renewables by 2050, but also all of its heating/cooling and transport fuel needs.

As with the studies above, it assumes a major commitment to energy saving[21], with a rapid rise in renewables, with an average annual growth rate of renewable electricity capacity of 14% between 2007 and 2020, and then an even more rapid expansion of some options.

Between 2020 and 2030, geothermal electricity is predicted to see an average annual growth rate of installed capacity of about 44%, followed by ocean energy with about 24% and Concentrated Solar Power (CSP) with about 19%. This is closely followed by 16% for Solar Photovoltaic (PV), 6% for wind, 2% for hydropower and biomass with about 2%. By 2030, total installed renewable capacity amounts to 965.2 GW, dominated in absolute terms by PV, wind and hydropower. Between 2020 and 2030, total installed renewable capacity would increase by about 46% with an average annual growth rate of 8.5%. And after 2030, expansion continues leading to almost 2,000 GW of installed capacity by 2050.

1.3.3 The World as a whole

The German Energy Watch Group [Energy Watch Group, 2008] claims that (non-hydro) renewables could supply 62% of global electricity, and 16% of global final heat demand, by 2030.

In November 2009, a scenario was published in the 'Scientific American' [Jacobson and Delucchi, 2009], which suggested that 100% of global energy could be obtained from renewables by 2030[22], with electricity also meeting heating and transport needs.

As can be seen, 100% reliance on renewable energy is apparently technically and economically feasible even on a global scale, but it is predicated on the will to unilaterally move to a carbon-free world, which is itself predicated on the perceived need to move to a carbon-free world.

As stated previously, there are three main reasons to dispense with conventional power:

1. It will run out
2. It is bad for our health, and

---

[21] The EREC claims that energy use can be reduced by 30% against the consumption assumption for 2050.

[22] Although it was claimed that 100% was technically feasible by 2030, in the conclusion it was qualified to, '*with sensible policies*', nations could set a goal of generating 25% of their new energy supply from renewables '*in 10 to 15 years and almost 100% of new supply in 20 to 30 years*'. But they insisted that '*with extremely aggressive policies, all existing fossil-fuel capacity could theoretically be retired and replaced in the same period*' although, '*with more modest and likely policies full replacement may take 40 to 50 years*'.

3. It plays a significant part in causing global warming.

Of these three reasons, the most highly-charged and politically-contentious is the association with global warming and climate change.

The radio programme 'Uncertain Climate' [Harrabin, 2010] concluded that there were several issues around climate change and global warming that were not well communicated and/ or understood. These included that:

- The public under-estimate the degree of consensus among scientists that humans have already contributed towards the heating of the climate (only around 3% disagree), and will almost certainly heat the climate more.
- Politicians and the media often fail to convey the huge uncertainty over the extent of future climate change[23].
- Although the great majority of scientists fear that computer models suggest we are facing potentially catastrophic warming, some climate scientists think the warming will be restricted to a tolerable 1ºC or 1.5ºC.

When faced with the size of the reaction required to mitigate climate change (especially the disruption, and effort required to move to 100% renewables as explained above), there has apparently been a desire for a convincing and unequivocal case to underpin this (frequently political) decision.

It is currently not clear with the current prediction technology whether the 'Climate Change Debate' will ever provide the required degree of certainty to underpin that political decision. The potential to achieve the clarity of understanding required has also been undermined recently by issues such as 'climate gate' and the probability of 'IPPC predictions'[24] where the effort to manage the public consumption of uncertainty and the presentation of results based on 'grey' (un-peer reviewed literature) respectively has brought the integrity of the scientists and the quality of the underlying science, into question.

---

[23] In essence that the media, allow little room for doubts and uncertainties – several examples were quoted of ranges of results, and words such as 'likely', 'probably' etc, being removed from media reports to provide a concise conclusion where in fact there was not a concise definitive conclusion, only a most probable one. This means that while there is scientific evidence for holes in the ozone layer, rising temperatures and changing rainfall patterns, there are degrees of uncertainty about inferring their causes, rate of change and scale of danger, the media considered it simpler for the public to understand 'Yes it is' or 'No it isn't', and the arguments between these two camps are usually attributed to 'Believers' or 'Sceptics'.

[24] A recent report from the Intergovernmental Panel on Climate Change contained a highly contentious claim about the speed at which glaciers in the central and eastern Himalayas are melting. This prediction was based solely on a 10-year article. 'Flooded Out', reported in the New Scientist by Fred Pearce. 5 June 2009. Issue No 2189, which was further extrapolated to include all glaciers in the Himalayas and quoted as being 'very likely', i.e. more than 90% certain.

1.4 Conclusion

The prospects for a 100% conversion or part conversion to renewable energy, although apparently technically achievable, appear to be limited in the short term unless it makes justifiable sense to implement it on:

- Financial grounds
- Health and Safety grounds, or
- Socially/ Political grounds.

It is concluded that, although it is still worth pursuing a 100% conversion in the long term as there are no obvious examples that are immediately encouraging for full scale conventional fuel replacement in the short term, there is a more immediate need and benefit in identifying a stand-alone discrete fundamental use for renewable energy on a significant scale that can be implemented in isolation, without reliance on conventional power sources. Therefore, this research attempted to define and model a power plant that not only has the potential to demonstrate that renewable energy has potential to stand alone as an un-supported power source in a justified manner, but also on a significant scale as an interim step on the road to 100% replacement of conventional power sources.

This is especially relevant to developing communities where it could meet new needs for power rather than acting as a replacement for existing conventional power sources.

The following chapter of this thesis details the uses renewable energy could be put to.

2 The use of renewable energy.

Having decided to employ renewable energy, the question now was what to use it for that:

- Would meet a fundamental human need, and
- Represent a significant scale of use.

The first step was to decide what the most fundamental human need is. Maslow's hierarchy of needs[25] was investigated to identify the fundamental human need that renewable energy should be used to address.

2.1 Maslow's hierarchy of needs

At its most basic conceptual level, Maslow's hierarchy of needs shows that each of us is motivated by needs, which can be represented graphically as a five-stage model[26], shown below in Figure 1.
To satisfy the most fundamental needs, the application of renewable energy should be as low down the triangle as possible, i.e. for the satisfaction of biological and physiological needs, such as air, sleep, food, warmth and drink (water).

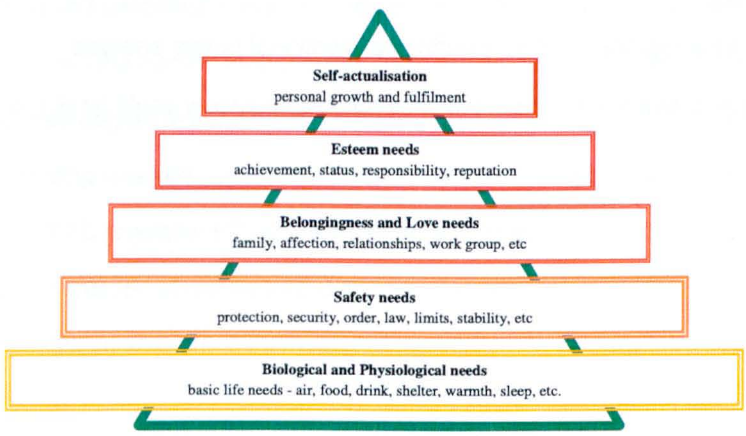

Figure 1: Maslow's hierarchy of needs five stage model

---

[25] Maslow's original Hierarchy of Needs model was developed between 1943 and1954, and first widely published in Motivation and Personality in 1954.

[26] Maslow's Hierarchy of Needs provides three fundamental rules which have been applied to all areas that require motivation:

- That we must satisfy each need in turn, starting with the first, which deals with the most obvious needs for survival itself.
- Only when the lower order needs of physical and emotional well-being are satisfied, are we concerned with the higher order needs of influence and personal development.
- Conversely, if the things that satisfy our lower order needs are swept away, we are no longer concerned about the maintenance of our higher order needs.

This section assesses the fundamental human needs presented by Maslow's hierarchy in terms of:

- How fundamental the need is
- What the most pressing problem with it is
- The potential to use Renewable Energy to alleviate this pressing problem.

2.1.1 Air and sleep

Air and sleep are clearly essentials for life but are not primarily dependent on use of energy. The main contribution that renewable energy could make to these is to reduce the level of pollution and consequent health impacts.

2.1.2 Food

Food once again is fundamental to us as human beings, and if deprived of it, we would starve and die. The most pressing problem faced by the world at the moment with food is of there not being enough to feed everyone, especially with predicted increases in population shown below in Table 4.

By the Food and Agriculture Organisation's [FAO, 1996] estimate, based on population growth and changing eating habits, the world will require several times the current food productivity by the year 2050. Africa will require over five times as much, and the world as a whole will require more than twice as much food as it did in 1995.

Table 4: FAO Food Demand Forecast (2050 /1995 Comparison in multiples of 1995 demand)

	Africa	Central and South America	Asia	North America	Developing Countries	Developed Countries	Globally
Population Increase	3.14	1.80	1.69	1.31	1.95	1.02	1.76
Changing Eating Habits	1.64	1.07	1.38	1.00	1.40	1.00	1.28
Total	**5.14**	**1.92**	**2.34**	**1.31**	**2.74**	**1.02**	**2.25**

The other significant problem with food supply is its reliance on energy. Vast amounts of oil and gas are currently being used as raw materials and energy in the manufacture of fertilisers and pesticides, and at all stages of food production, including:

- Planting
- Irrigation
- Feeding
- Harvesting
- Processing
- Distribution, and
- Packaging.

In addition, fossil fuels are essential to facilitate this industry, including operating farm machinery, processing facilities, storage facilities, ships and trucks. The industrial food supply system is one of the biggest consumers of fossil fuels, and one of the greatest producers of greenhouse gases, with energy use by Americans for food making up 12% to 17% of total current American energy usage [Minn, 2009]. It is noteworthy that this energy usage in food production and distribution is to achieve a higher level in Maslow's triangle, i.e. what the developing world aspire to. Food production at the fundamental level of Maslow's triangle is dependant upon water production.

It is not clear that there is any significant application of renewable energy that could be used to directly address the fundamental human need for food.

2.1.3 Warmth

As human beings we need to maintain a state of homeothermy at a core temperature of about 37°C, and in many cases this requires that internal spaces are heated and/ or cooled.

The majority of space heating is achieved using conventional fuel, but examples of the use of renewable energy on a large scale for space heating and cooling is presented at 'Renewables in district heating and cooling' [Euroheat and Power]. This document illustrates a variety of renewable energy sources used in European district heating infrastructures to warm and cool human living spaces.

It is evident that renewables can be employed on a significant scale to meet the human need for a temperature-controlled environment, and when combined with energy use minimisation initiatives, can make efficient use of renewable energy.

2.1.4 Water

Without water, we as human beings would die. It is the very essence of our being making up some 60% by mass of our bodies.

Although water is in abundance on Earth, there is only a limited amount of water available for human consumption that is renewable, as shown by Table 6 below, adapted from 'the Global Water Cycle' [Berner and Berner, 1987].

2.1.4.1 Water for human use

Although water is the most widely occurring substance on earth, it can be seen from Table 5 below that only 2.75 percent is freshwater, while the remainder is oceanic salt water.

Over two thirds of this freshwater is locked up in glaciers and permanent snow cover which leaves less than 1% available for human consumption[27].

In addition to the accessible freshwater in lakes, rivers and aquifers, storage in reservoirs adds a further 8,000 cubic kilometres (km^3).

Table 5: Global water reservoirs and their proportions.

Reservoir	Volume (in millions of cubic kilometres)	Percent of total
Oceans	1370.0	97.25
Ice caps and glaciers	29.0	2.05
Deep groundwater[28] (750-4,000 metres)	5.3	0.38
Shallow groundwater (less than 750 metres)	4.2	0.30
Lakes	0.125	0.01
Soil moisture	0.065	0.005
Atmosphere[29]	0.013	0.001
Rivers	0.0017	0.0001
Biosphere	0.0006	0.00004
Total	**1408.7**	**100**

Precipitation is the main source of water for all human uses and for ecosystems.

This precipitation is taken up by plants and soils, it then evaporates into the atmosphere via evapotranspiration, and then runs off to the sea via rivers, and to lakes and wetlands[30].

The percentage of appropriated water is increasing, but there are several issues including the legal limitations on abstraction, and the global disparity of the distribution of this water.

2.1.4.2 Further constraints on water use

The availability of these renewable sources for human use is further constrained by:

- Environmental legislation
- Global disparities between availability and demand for water
- The envisaged increase in human demand for water, and
- The potential impact of global warming.

Appendix A of this thesis gives greater detail of these constraints, and it is evident that:

- There are increasing legal limitations (particularly in developed countries) on the water that can be abstracted.

---

[27] Water that is not deep underground, trapped in the soil or biosphere/ atmosphere.

[28] The total interstitial water in the pores of sediments is in the order of 50-300(10^6) km^3.

[29] As liquid equivalent of water vapour.

[30] The water of evapotranspiration supports forests, rain-fed cultivation and grazing lands, and ecosystems. As human beings, we are also gaining greater control of both runoff and evapotranspiration and are becoming ourselves significant players in the hydrological cycle.

- There are many locations in the world (particularly in developing countries) with disproportionately small amounts of water available considering the volume of people being served.

The developing world will:

- Require substantial water supplies for irrigation for food production to feed their fast-growing populations, and
- Potentially suffer the greatest impact on their water supplies due to global warming and climate change.

These constraints are causing significant hardship, and the need to supply water to many in the world is not being met. In many cases, those most in need of water today are likely to experience an increased need, and suffer the most lethal and severe impacts on their water supplies, due to the effects of climate change.

2.1.5 Conclusion

Although there are avenues that could employ renewable energy to meet a fundamental human need, specifically space heating/ cooling and food production, these mainly address comfort and convenience requirements.

There is a need at a fundamental level on Maslow's triangle which is not being addressed, which is the provision of water to those most in need.

Therefore this research investigated renewable energy for water production for human consumption.

2.2 How could Renewable Energy be used to increase water supply for human consumption?

Figure 2 below provides an overview of the constraints on water for direct human consumption. These include:

The limited amount initially available for consumption

- The expected reductions as Global Warming impacts are felt
- The amount needed for irrigation, and
- The amount needed for industry.

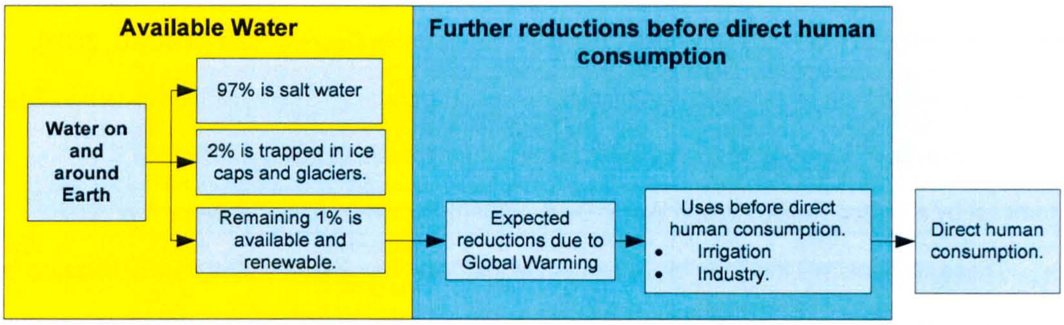

Figure 2: Water available and reductions before human consumption

The limitations on the renewable water available and potential impacts of global warming, are explained at Appendix A. This section will concentrate on water for food production and for industry. Food production and industry use a significant amount of water, and the amount of water used in each of these areas is variable, depending on the economic status of the area.

2.2.1 Water for food production

Food production is particularly intensive in its water use, and that it is likely that developing countries (already experiencing limited water supply issues), will experience the greatest increase in water demand to feed their fast growing populations.

The main source of the world's food supply is agriculture, which includes crops, livestock, aquaculture and forestry. Unmanaged earth systems can only feed a fraction of the current world population, so systematic agriculture is essential.

2.2.1.1 Maintaining food supply

The water requirement for most agriculture is met directly by rain, but irrigated land accounts for about one fifth of the total arable area in developing countries. Some 15 percent of agricultural water is used by irrigation, totalling about 2,000-2,500 km^3 per year. In 1998, in developing countries, irrigated land produced two-fifths of all crops, and three-fifths of all cereals. Cereals are the most important crop, providing 56 percent of calories consumed worldwide [FAO, 2003]. Developed countries account for about 25 percent of the world's irrigated areas, but their populations have relatively slow growth. So, the greatest irrigation development is expected to occur in the developing world, where population growth is stronger.

2.2.1.2 Irrigation water use

Currently, according to the World Business Council for Sustainable Development [WBCSD, 2009], irrigation accounts for 70 percent of all water withdrawals, and several nations (India, China and Egypt) are using in excess of 90 percent of their water to meet irrigation needs.

It is forecast by a United Nations World Water Development Report [UNESCO], that:

- These amounts will increase by 14 percent in the next thirty years, as the area of irrigated land expands by a further 20 percent
- By 2030, 60 percent of all land with irrigation potential will be in use, and of the ninety-three developing countries surveyed by FAO, ten are already using 40 percent of their renewable freshwater for irrigation. 40 percent is taken as the level at which difficult choices can arise between agriculture and other users
- By 2030, it is estimated that South Asia will have reached this 40 percent level, and Near East/North Africa will be using about 58 percent
- However, for sub-Saharan Africa, Latin America and East Asia, irrigation water demand will be below the critical threshold although at local level, serious problems may arise.

2.2.1.3 Water use in food production

Table 6 below shows the volume of water used in the production of a variety of foodstuffs.

It is clearly apparent that:

- A large amount of water is required to produce our food, and
- Cereals, oil crops and pulses, roots and tubers consume far less water per unit than meat[31].

[31] Meat production requires large amounts of grain to be used as feed for the animals. The production of 1kg of beef requires 11kg of grain (using corn as the measure), and one kilogram of pork or chicken requires 7kg and 4kg of grain respectively.

Table 6: Water requirement of main food production.

Product	Unit	Equivalent water in cubic metres based on FAO estimates*	Equivalent water in cubic metres based on New Scientist estimates
Bovine, cattle	head	4,000	
Sheep and goats	head	500	
Coffee	kilogram		20
Meat bovine fresh	kilogram	15	
Meat	burger[32]		11
Meat sheep fresh	kilogram	10	
Meat poultry fresh	kilogram	6	
Cheese	Kilogram		5
Rice	Kilogram		5
Sugar	kilogram		3
Palm oil	kilogram	2	
Milk	litre		2
Cereals	kilogram	1.5	
Citrus fruit	kilogram	1	
Pulses, roots and tubers	kilogram	1	

*[FAO, a]

** [Pearce, 2006]

2.2.1.4 Current situation

Worldwide, the total irrigated land surface has increased five times from 50 million hectares in 1950, to 250 million hectares in 1998. Also, according to the [FAO, a], there is a strong positive relationship between urbanisation and increased incomes, and water intensive food (particularly meat) consumption.

2.2.1.5 The Future

In light of the expected population increase and trend towards more water intensive foodstuffs, due to increased urbanisation and available income, it is not clear what corresponding agricultural land will be required (or be available) to support it.

The July 2011 edition of the UNEP Global Environmental Alert Service (GEAS) [UNEP, 2011] gives an indication of:

- The current activities currently being undertaken to ensure adequate land is available (mainly richer countries buying land with established water supplies in poorer countries), and
- Some of the potential risks associated with these activities, including:
  - Negative impacts on local environments, forests, pastures and woodland, and

[32] Unit for the burger is 'Quarter Pounder'. As such, it is apparent (if the figures from the different sources are correct) that processed foods use a greater amount of water than non-processed foods, i.e. 1kg of meat requires 15 cubic metres of water in comparison to a quarter pounder (approximately 1/8th of a kg) which requires 11 cubic metres.

- Marginalisation of communities due to disparity of compensation within potentially un-transparent planning consents.

2.2.2 Water for industry

Industry is particularly intensive in its water use, and it is likely that developing countries (already experiencing limited water supply issues) will experience the greatest increase in water demand as they industrialise to give their populations a better standard of living.

Global annual water use by industry is expected to rise from an estimated 725 km^3 in 1995 to about 1,170 km^3 by 2025, by which time industrial water usage will represent 24 percent of all water use. Much of this increase will be in developing countries now experiencing rapid industrial development. Figure 3 below [UNIDO, 2008] shows industrial water usage per region, compared with other main uses. It indicates quite clearly that the trend is for industrial use of water to increase with a nation's income, going from 10 percent for low- and middle-income countries, to 59 percent for high-income countries.

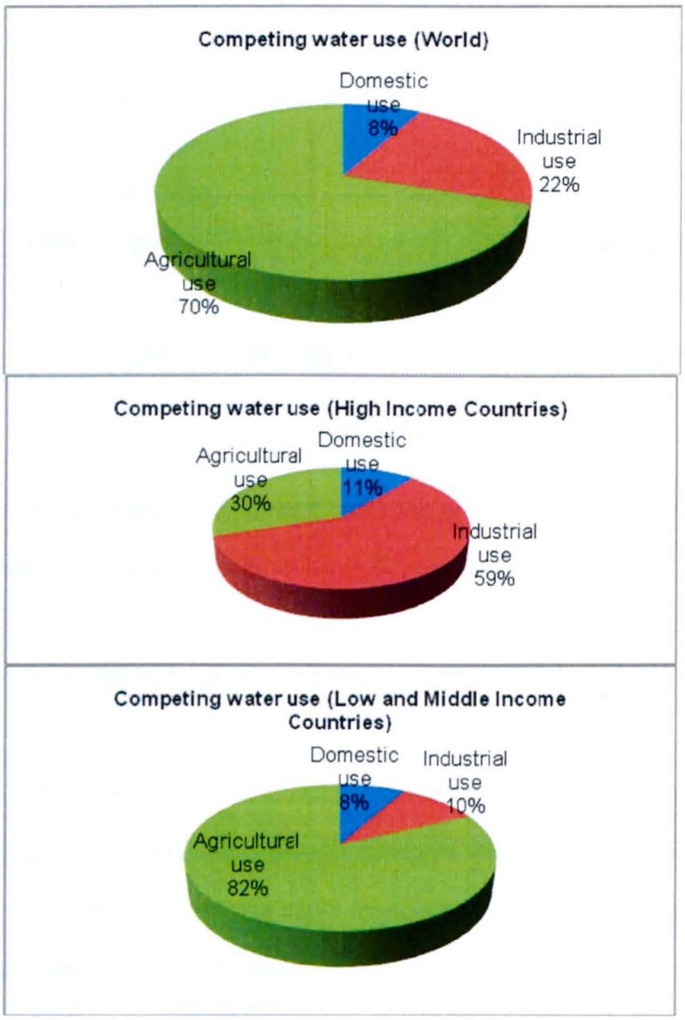

Figure 3: Competing water uses for main income groups of countries.

Figure 4 below shows the typical proportions of personal water use in an office and it is noteworthy that almost two-thirds of the water is used in toilets.

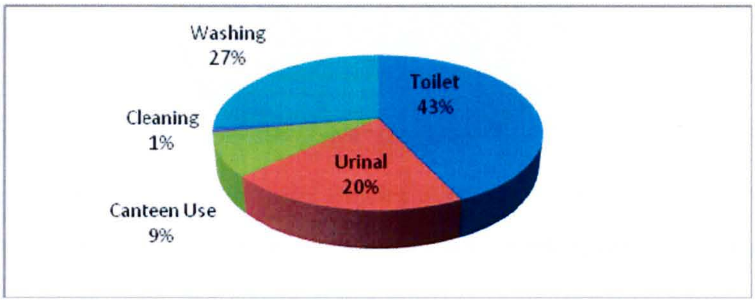

Figure 4: Domestic water use in a typical office

So, as the developing nations industrialise they will most likely use more water, not only for industrial process, but also for personal use.

2.2.3 **Domestic freshwater use**

Globally, domestic freshwater use accounts for around 8 per cent of withdrawals, or 120–200 litres per person/day. In many large cities in developed countries, municipal freshwater withdrawals providing for the immediate needs of local small businesses and households alone, amount to 300–600 litres per person per day. Meanwhile, the equivalent figure for Asia, Africa and Latin America approximates to only 50–100 litres per person per day.

2.2.3.1 Minimum water required

The minimum amount of water required to meet basic needs varies depending upon what is included as "basic needs". The figures vary from 20[33] [WHO/UNICEF, 2000] to 50 litres per person per day [Abrams, 2001], and attempts to standardise the minimum level to be provided have not always been successful[34]. Figure 5 below, based on [WHO/UNICEF], shows the distribution of the world population not served by water supply infrastructure. Although Asia shows the highest number of people not served, it is important to note that proportionally (in percentage of population terms), this group is larger in Africa due to the difference in population size between the two continents[35].

---

[33] The WHO/ UNICEF defines reasonable access to water as at least 20 litres per person per day, from an improved source within 1 km of a user's dwelling.

[34] An example where attempting to set strict standards was shown to be counter-productive was in South Africa where insistence on both affordability and a predetermined standard of 25 litres per person per day were mutually exclusive, resulting in some poorer communities not being serviced – The policy has subsequently been changed.

[35] 1.01 billion not served with clean water:
- 65% in Asia. 0.715 Billion (20% of Asia's population on 1996 population figures), and
- 27% in Africa. 0.297 billion (40% of Africa's population on 1995 population figures).

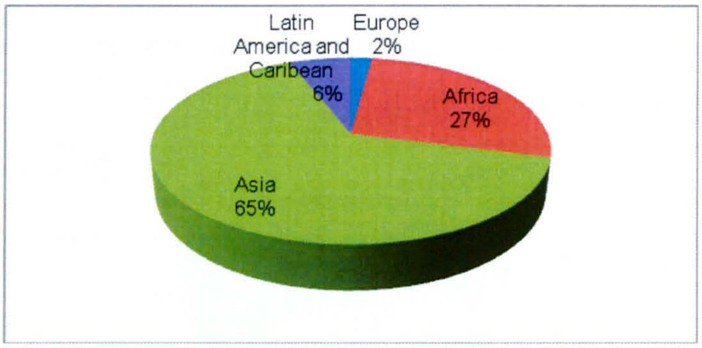

Figure 5: Water supply distribution of populations not served by water supply infrastructure.

Currently, 1.1 billion people lack access to an improved (or local, clean) water supply and 2.4 billion to improved sanitation, and are invariably the poorest in society. According to the World Health Organisation [WHO/UNICEF, 2002], relatively minor effort could drastically improve the situation[36]. If improved water supply and basic sanitation were extended to those currently not served, it is estimated that the burden of infectious diarrhoeas would be reduced by some 17 percent annually; if universal piped, well-regulated water supply and full sanitation were achieved, this would reduce the burden by some 70 percent annually.

2.2.3.2 Expected increase in domestic water use in developing countries

A typical breakdown of the domestic, drinking and cooking use of water in the home in the developed world is illustrated below in Figure 6, based on [Thornton, 2005].

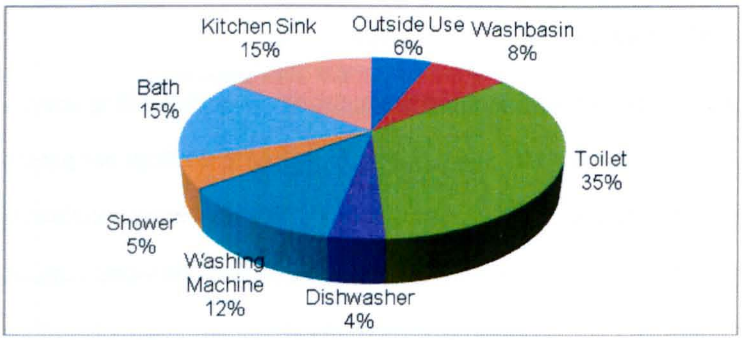

Figure 6: Domestic water use in a typical house.

It is noteworthy that, in comparison to developing countries:

- Toilets account for more than one third of water use, and with increased sanitation in the developing world, this will result in greater demand for water resources
- Baths and showers account for around one fifth of the water used, and

[36] Relatively minor improvements would also lead to reductions in other water, sanitation and hygiene related diseases, such as schistosomiasis, trachoma and infectious hepatitis.

- An improved economic situation will result in more baths and showers in the developing world, and an equivalent rise in water use.

Washing machines and dishwashers account for around one-sixth of water use, and an improved economic situation will result in more washing machines and dishwashers in the developing world, and an equivalent rise in water use.

Developing nations with reduced sanitation and installed washing facilities only use perhaps 1/3rd of the water supply used by developed nations, but as they achieve developed world incomes, they will aspire to water use to match their quality of life, i.e. increasing water use by at least three times per typical household.

2.2.4 **Conclusion**

European freshwater consumption for an individual is shown below in Figure 7 for annual water withdrawal[37] [SwissRe, 2010].

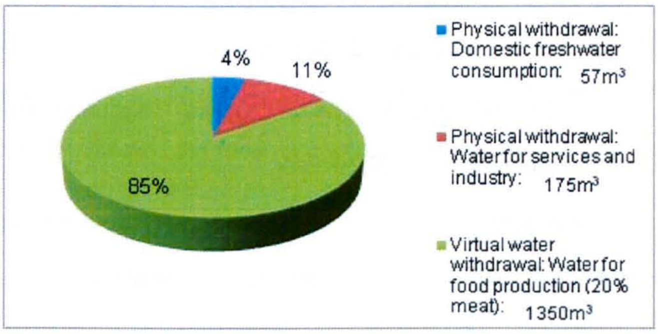

Figure 7: Total annual water withdrawal per person: 1500-1800m³

It can be seen from Figure 7 above that 85% of the water consumed by the average European (the levels that the developing world will aspire to) as food. In reaching this aspirational level, the developing world is likely to industrialise (as shown in Figure 3 above). This combination of increased consumption of water intensive foodstuffs and industrial expansion, will place an increasing burden on water supplies for direct human consumption.

Also, having improved their standard of living by industrialisation, developing countries will aspire to sanitation levels and labour-saving conveniences in line with developed countries, which will cause further demand on their limited water supplies, which as stated previously, are disproportionately susceptible to the impacts of climate change.

---

[37] This estimate takes into account the additional element of 'virtual water'. This is the theoretical equivalent of freshwater used for food production to meet the nutritional requirements of a European adult (average net income), 20 per cent of whose diet consists of meat. Total: approx. 1,600 m^3.

2.2.5 Water Supply and Renewable Energy.

There are five key areas where changes could make a difference to the water supply:

- Increasing the amount of renewable water available
- Mitigating the impact of Global Warming
- Managing food production
- Managing direct human use of water, and
- Wastewater treatment to enable water reuse.

2.2.5.1 Increasing the amount of renewable water available

This option would entail the use of renewable energy to desalinate seawater to potable water quality.

2.2.5.2 Mitigating the Impact of Global Warming

The mitigation of the expected impacts of Global Warming by using renewable energy to operate a desalination plant would address a fundamental human need, but would not on its own reverse the current greenhouse gas loading in the atmosphere, since it is only one area of energy use. Nevertheless it is an important area, as has been indicated, for a range of social reasons as well as being one way in which some Green House Gas production can be avoided.

Renewable energy supplies may gradually become more widely available via power grids, and could in time displace the majority, if not all, of the emissions from conventional fuels, as discussed in section 1.3, in which case some of it could be used for desalination. In the meantime, it is concluded that, in light of the aim of this work, which is primarily to support a growing water requirement without a proportionate increase in CO_2, that a free standing, renewable energy driven, desalination plant could make a contribution to managing climate change.

2.2.5.3 Managing food production

Initiatives are in place for more water-efficient, genetically-modified crops, and there is no obvious avenue to employ renewable energy beyond the logistic aspects.

2.2.5.4 Managing direct human use of water

It is apparently inevitable that as the global population increases in size, and become, more affluent, that water use will increase. Once again, there is no obvious avenue to employ renewable energy directly.

2.2.5.5 Wastewater treatment to enable water reuse

Renewable energy could be used to power wastewater treatment processes, to produce water that can be reused.

The debate whether to treat waste-water for reuse or desalinate, has been presented to the International Water Association [Hind, 2007], but it is only considered viable for developed nations with extensive waste-water management infrastructure.

The reuse by industry is the preferred route at locations with sophisticated waste-water treatment infrastructure, as there is an economic driver for industry to use the recovered water, which has a higher value than potable water.

This is due to the low salinity levels of the recovered secondary effluent product. These would be lower than that in potable water. Potable water would require further ion exchange treatment to achieve a similar quality. The example quoted by Martin Hind is where a water recovery plant was installed at Flag Fen Sewage Treatment Works to supply low salinity water to the local power station, resulting in reduced ion exchange treatment costs for the boiler feed water at the power station [Alpheus].

This said, the aim of this research was to assess the viability of providing water for direct human consumption, as this was identified as the most fundamental need, with the highest priority.

2.2.6 Decision

This research thus focussed on the use of renewable energy for the desalination of seawater to produce potable water for domestic use.

As shown in Figure 8 below, this would:

- Reduce the risk of disruption due to Global Warming
- Maintain food production, and
- Deliver a dedicated water supply directly to the user.

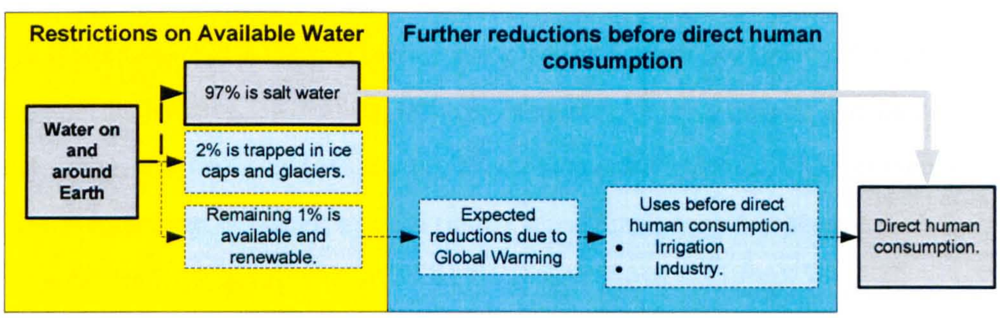

Figure 8: Revised water supply system

It is also noteworthy that desalination has the additional benefit of not having a time dependent power demand if batch production and storage of fresh water on site is used. The ability, to effectively store power produced in excess of immediate requirements as water, should tend to reduce the impact of the intermittency of the renewable energy supplies being employed.

2.3 Where should desalination be employed and what type of desalination should be used?

It is apparent that certain regions are more in need of water than others by Desalination due to the following:

- Limited initial supply – Desalination would bypass (or significantly reduce the vulnerability to) the issue of limited conventional water supplies for the user group
- Global warming – Desalination would ensure a dedicated supply to the user, with less risk of being compromised by local extreme weather events
- Water demand for food production – Desalination would provide a dedicated supply for direct human use, without impacting on the water supply used for food production
- Increased domestic water use – Desalination would reduce the risk associated with expected higher water use from existing resources as the economies of the developing world grow
- Demand from industry – Desalination would supplement conventional supplies for industry.

Table 7 below:

- Consolidates the issues that additional water supplies using desalination would address, and
- Indicates the locations that would benefit most.

Table 7: Consolidation of locations for desalination

Issue		Location	Reason
Limited initial water supply	Available global water vs. proportion of population	Asia	36% of water, with 60% of population
		Africa	11 % of water, with 13% of population
		Europe	8% of water, with 13% of population There are local renewable water availability issues in south east England, which has limited rainfall combined with legal abstraction limitations.
	Water supply coverage	Asia	Mongolia and Chinahave51% – 75% water supply coverage. India and Iran have 76 – 90% coverage. 1.01 billion people without water supply coverage – 65% of the global population.
			Has 65% of the global population not served by water supply (0.715 Billion). Equates to 20% of Asia's population, based on 1996 population figures.
		Africa	Somalia and Ethiopia have virtually no water supply coverage. Only southern Africa (South Africa, Zimbabwe and Angola) has better than 75% coverage, with the rest of the continent being below 75%, and a third below 50%.
			Has 27% of the global population without water supply coverage (0.297 Billion). Equates to 40% of Africa's population based on 1995 population figures.
Global warming impacts	Vulnerability to water related disasters	Asia	Affected by 35% of water related disasters. Together suffer 97% of fatalities due to natural disasters
		Africa	Affected by 29% of water related disasters.
	Water scarcity	Asia	Will most likely suffer the brunt of water scarcity due to climate change.
		Africa	
Food production	Need for irrigation in 2030 (increase in food demand by 2050)	Asia	South Asia will have reached 40% usage of available water supplies. (Will require 2.34 times as much food)
		Africa	Near East/ North Africa will have reached around 58% usage of available water supplies. (Will require 5.14 times as much food)
Domestic use	Expected increase in domestic use	Asia	Municipal fresh water withdrawals amount to 50 – 100 litres/ person/ day. This figure will tend towards the 120 – 200 l/p/d global average, and probably further to the 300 – 600 l/p/d of the developed world.
		Africa	
		Latin America	
Industrial use	Expected increase in industrial use	Asia	To achieve the industrial growth to sustain the projected increases in their populations, the developing world will need to industrialise. It is highly likely that manual manufacturing (more water intensive) processes will migrate to the developing world, causing an increase in industrial water demand.
		Africa	
		Latin America	

2.4 Conclusion

The areas in the greatest need for such a facility, are Asia and Africa from the evidence presented in Table 8 above.

For the purposes of this thesis, the research will focus on Africa based on the:

- Estimated increase in food demand, and
- Its limited water supplies.

Millions of people have died in the 20th century due to severe drought and famines. One of the worst hit areas has been the Sahel region of Africa, which covers parts of Eritrea, Ethiopia and the Sudan, and at the time of writing, another drought has recently affected the eastern Horn of Africa, as reported within the UNICEF progress report 'Response to the Horn of Africa Emergency. A continuing crisis threatens hard-won gains' [UNICEF, 2012].

This thesis will investigate water production for Eritrea. This nation has been selected due to its susceptibility to droughts, and consequential loss of life. Eritrea has a substantial coastline, and the sea level rise expected due to climate change will most probably exacerbate the intrusion of saline water into the fresh groundwater aquifers in the coastal zone. The focus of this research will be Massawa, which is in a particularly dry part of Eritrea.

Water supply using desalination at Newhaven in South East England will also be investigated, as this is a particularly dry part of the United Kingdom.

2.4.1 Comparison of sites

The comparison of these two sites for desalination gives an extreme contrast as Massawa has limited water and power infrastructure to call upon, whereas Newhaven is supported by an extensive national water supply and power distribution network.

2.5 Eritrea

Eritrea (map shown below in Figure 9) lies in the Sahelian belt, which is characterised by frequent and prolonged droughts. The country suffered the latest drought in 1993. It is observed that the drought has been repeating itself every 5-7 years, although interestingly Eritrea did not declare a drought during 2011, which was a source of heated debate itself [Howden, 2011].

It has been observed that weather patterns in Eritrea started changing greatly in the 1960s, and as a result of these changes, arid and semi-arid regions of the world, including countries like Eritrea, are projected to be more vulnerable to the adverse effects of climate change than others. Farmers have observed that the duration of the rainy season has been reducing for the last two or three decades, and this is resulting in changes in the spatial and temporal availability of water resources throughout the country. These observations however need to be substantiated by detailed studies. The observations are in agreement with the widely-held belief that climate change is affecting the global hydrologic cycle in general, and precipitation and runoff in particular.

In Eritrea, rainfall is erratic and torrential, and quickly forms heavy floods, with little chance of penetrating into the ground, although efforts to harvest rain-water are being undertaken [Self Help Africa]. Perennial streams hardly exist with the River Setit being the only perennial river, and there are no lakes. The potential of underground water resources is still not clearly studied and documented. Moreover, meteorological and hydrological information, which is critical for any water resource development activity, is at its early stages of development. Meteorological data collection started during the Italian colonial period (1890- 1941), and before the 1930's more than 20 meteorological stations were in operation throughout the country. At the time of independence (1991), however, only two stations were operational. The lack of time series of hydrological and weather data gaps have therefore made water studies difficult. Currently there are around 160 weather stations distributed throughout the country.

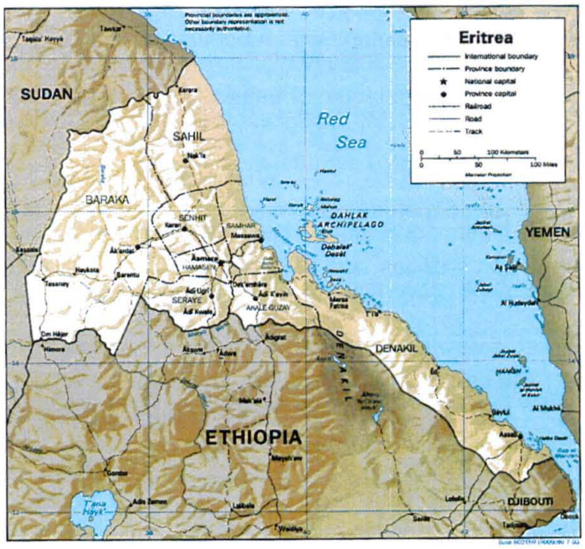

Figure 9: Map of Eritrea in relation to Ethiopia and Sudan

As can be seen from Figure 10 below, Eritrea is split into distinct regions, based on rainfall, and it can be seen that the Red Sea region where Massawa (also known as Mits'iwa) is situated (highlighted in yellow), has the lowest rainfall.

Extreme altitude variations, ranging from sea level to around 3000m above sea level, continental pressure changes, and other factors, determine the climate of Eritrea.

Most parts of Eritrea receive uni-modal rainfall, and the rainy season extends from June to September, although there are less heavy rains that start in April/May. Rainfall increases from north to the south of the country, varying from around 200mm in the North Western Low Lands, to around 650mm in the southern part of the Central Highlands.

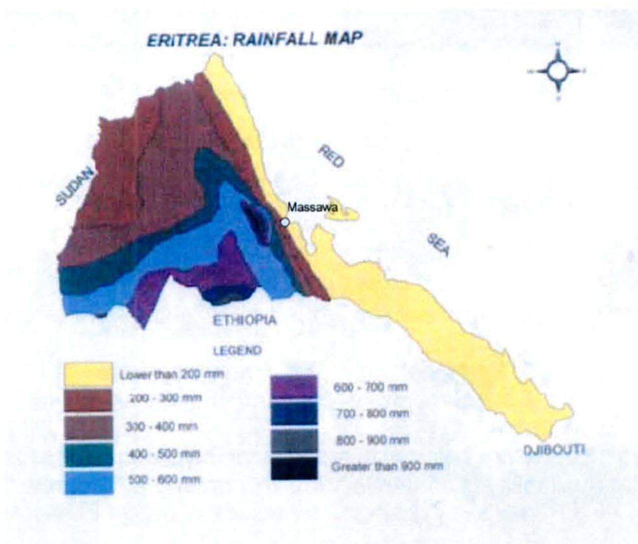

Figure 10: Expected rainfall in Eritrea

Massawa is the second largest town, and the main port, in Eritrea, situated on a small sterile coral island in the Red Sea, around 200 m from the mainland with a population of 43,600 [Tekle and Ogbai, 2008]. It lies 65 km (40 miles) northeast of the largest town of Eritrea (Asmara) at 15 36N, 39 28E and there is an established rail link between the two towns.

It was selected as the site for renewable energy-powered desalination as it is compact, and in an area of low rainfall. The town has good port facilities, and therefore good potential for further industrial and economic urbanisation.

Activities in Massawa include salt production, fishing, fish and meat processing, and cement manufacture. Exports include oil seed, coffee, and cattle.

2.5.1 Variations in mean annual rainfall of Eritrea

Water was formerly scarce, in Massawa, with the mean annual rainfall less than 200mm, as shown above in Figure 10, but according to 'The State of Eritrea' [UNFCCC, 2001] in 1872 an ancient aqueduct from Mokullu (8km westward) was restored and the town is connected to the mainland by an embankment containing the water conduit from Mokullu.

2.5.2 Scenario to be modelled at Massawa

The aqueduct is considered to be at risk due to climate change i.e. weather, salinification, etc, and a new source of water is required for Massawa to allow continued habitation with confidence.

The requirement is for 7,000m^3/day of municipal water for 50,000 people. This equates to 140l/person/day, which compares favourably to the UK average water usage of 150l/person/day [Sims, 2006]. A desalination plant could satisfy that need.

2.6 South East England

According to the Daily Telegraph [Harrison, 2004] the UK on average, has only marginally more water available than that in Spain. However, 25% of the population of the UK resides in the South East of England where:

- The water availability falls dramatically to around 1/10th of the UK average, but
- The consumption in South East England is 15l/person/ day more than the UK average [Environment Agency, 2010].

For comparison, the water availability in Jordan in 1990 was around 20% greater than that in the south east of England.

The water scarcity problems have been exacerbated by population increases in the South East. Metering and reduced usage have been proposed. This will help stabilise demand but it is doubtful whether this will be sufficient, and as a partial solution, Thames Water has installed a 150,000m³/day desalination plant in the Thames estuary [Thames Water, 2010].

New reservoirs have also been proposed. However, this pre-supposes that there is sufficient rainfall to fill them. An example where there was not and piped distribution was required to increase the reservoir's catchment area is Bewl [Bewlwater]. Local water grids could help distribute the resources more evenly, but as shown in Figure 11, there is no area in the South East of England with abundant water supplies.

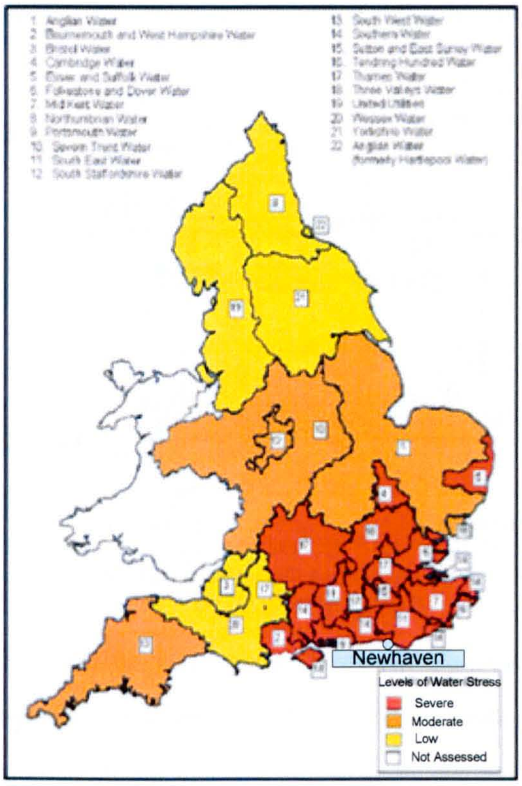

Figure 11: Levels of water stress in south east England

So, the benefit assessment of providing desalinated water in South East England using renewable power was also analysed as part of this research.

2.6.1 Scenario to be modelled in Newhaven

The scenario for South East England was to base a desalination plant in Newhaven to treat seawater, and act as the sole water source for 50,000 local users. It is noted that it would probably not be financially attractive to use an RO plant in southeast England in this way[38].

---

[38] According to Mr James Grinnell, formerly of Southern Water, the economics of running an RO plant on an 'as-needed' basis to supplement other supplies, as opposed to acting as the sole provider, significantly reduces the high operating costs

2.7 Type of Desalination to employ

The following desalination options were considered:

- Multi-Stage Flash (MSF) Distillation
- Multi-Effect Distillation (MED)
- Vapour Compression Distillation
- Reverse Osmosis Desalination.

2.7.1 Multi-Stage Flash (MSF) Distillation

Figure 12 below shows the Multi-Stage Flash (MSF) Distillation process based on the SIDEM web page[39].

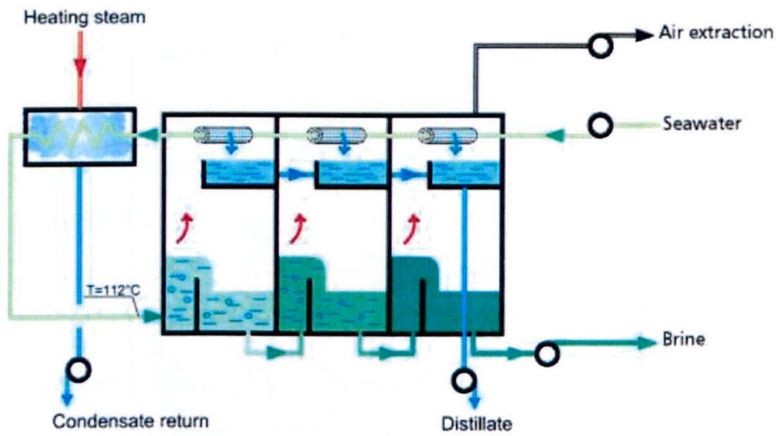

Figure 12: Multi Stage Flash (MSF) Distillation Process

An MSF system consists of several consecutive stages (evaporating chambers), maintained at decreasing pressures from the first stage (hot) to the last stage (cold). Sea-water flows through the tubes of the heat exchangers, where it is warmed by the condensation of the vapour produced in each stage. The sea-water then flows through the brine heater where it receives the heat from steam for the process. At the outlet of the brine heater, when entering the first cell, the sea-water is overheated, compared to the temperature and pressure of stage 1. It immediately boils to steam/ vapour, to reach equilibrium with stage conditions. The produced vapour is condensed into fresh-water on the cooler tubular heat exchanger at the top of the stage, and collected in a temporary holding tank. The process takes place again when the water is introduced into the following stage, and so on, until the last and coldest stage.

---

that are incurred from the RO process. The capital cost of RO desalination for providing the extra capacity compared to a reservoir that can yield 20ml/d are approximately 30% i.e. a reservoir yielding 20Ml/d and costing £50m, compared to a RO plant providing 20Ml/d costing £15m.

[39] The Multi-Stage Flash (MSF) Distillation process description is available at http://www.sidem-desalination.com/en/process/MSF/ [Last viewed on 7 August 2011].

The cumulated fresh water builds up the distillate production, which is extracted from all the previous temporary holding tanks at the coldest stage on the right.

2.7.2 **Multi-Effect Distillation (MED)**

Figure 13 below shows the Multi-Effect Distillation (MED) process based on the SIDEM web page[40].

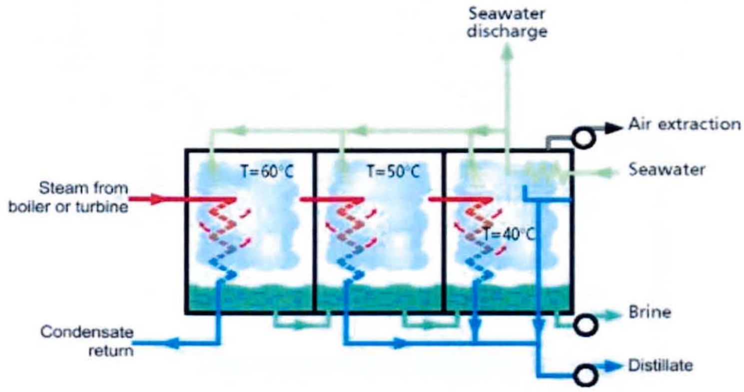

Figure 13: Multi Effect Distillation (MED) Process

The MED evaporator consists of several consecutive cells maintained at a decreasing level of pressure (and temperature) from the first (hottest at around 60C) to the last (coolest at around 40ºC). Each cell (also known as an 'effect') contains a horizontal tube bundle. The top of the bundle is sprayed with sea-water make-up that flows down from tube to tube by gravity. Heating steam is introduced inside the tubes. Since the tubes are cooled externally by make-up flow, steam from the previous stage condenses into distillate (fresh-water) inside the tubes. The heat released by the condensation (latent heat) warms up the sea-water outside the tubes, and partly evaporates it. Due to evaporation, the sea-water salt content concentrates slightly when flowing down the bundle, and gives brine at the bottom of the cell. The vapour raised by sea-water evaporation is at a lower temperature than heating steam. However, it can still be used as a heating medium for the next effect, where the process repeats. In the last cell, the produced steam condenses in a conventional shell-and-tube heat exchanger. This exchanger, called "distillate condenser" or "final condenser", is cooled by sea-water. At the outlet of the final condenser, part of the warmed sea-water is used as make-up of the unit. The other part is rejected to the sea. Brine and distillate are collected from cell to cell till the last one, where they are extracted by centrifugal pumps.

---

[40] The Multi-Effect Distillation (MED) process description is available at http://www.sidem-desalination.com/en/process/MED/ [Last viewed on 7 August 2011].

2.7.3 Vapour Compression Distillation

Figure 14 below shows the Vapour Compression Distillation Process.

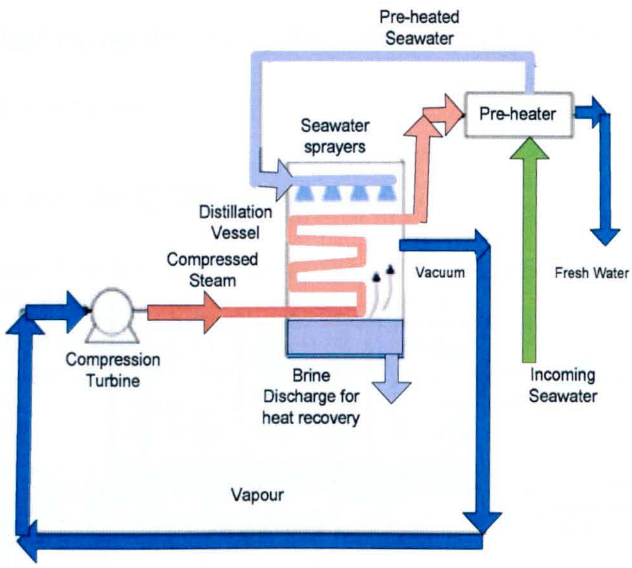

Figure 14: Vapour Compression Distillation Process

Vapour compression uses power a compression turbine, which draws vapour from the distillation vessel and compresses it.

This:

- Generates a vacuum within the distillation vessel, and
- Raises the temperature of the exhaust vapour.

The heated vapour is then used to heat the seawater (introduced by seawater sprayers) in the distillation vessel, which boils off to a vapour at low temperature, due to the vacuum within the distillation vessel.

It is then passed through the seawater pre-heater, where it returns to the liquid state as fresh-water.

The heat removed during condensation is returned to the incoming seawater to pre-heat and assist in the production of further vapour.

2.7.4 **Reverse Osmosis (RO) Desalination**

Figure 15 below shows the Reverse Osmosis Desalination Process, which is explained in the following text, and in greater detail later at section 4.1.

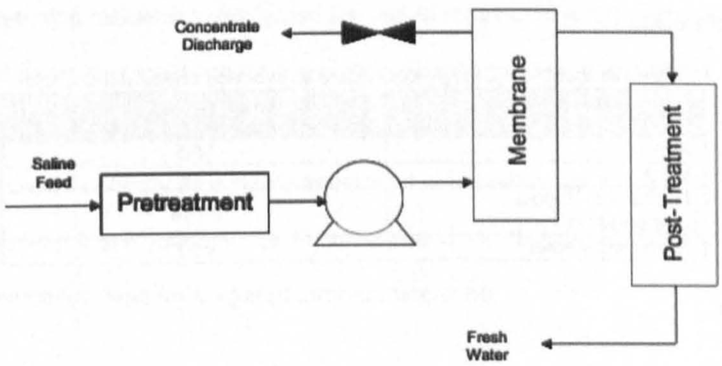

Figure 15: Reverse Osmosis Desalination Process

Reverse osmosis is a type of water desalination in which pressurised salt-water is passed through membranes which separate the salt from the water.

Reverse osmosis has four distinct steps:

1. Pre-treatment - in which solid impurities are removed from the salt-water, and chemicals inhibitors are added to adjust its pH level, and limit calcium sulphate scaling on the membranes
2. Pressurisation - in which the pre-treated water is pressurised
3. Membrane separation - in which semi-permeable membranes are used to separate salts from the pressurised sea-water, and
4. Stabilisation - in which the treated water is prepared for consumption.

Table 9 below shows the specific energy consumption to produce one cubic metre of water, by the various processes discussed. It can be seen that RO is currently the most energy efficient technology for seawater desalination. There are other considerations of course, particularly the capital and maintenance costs[41].

Nonetheless, the attraction of RO for renewable-energy powered desalination is already apparent, and the process is conditionally supported for renewable energy applications by the European Commission [Gerling, 2001], which concluded that RO was suitable for renewable applications, but was made

[41] RO is a relative newcomer and is considered by some to be less reliable, particularly with regard to fouling caused by difficult feed waters.

inefficient due to the requirement for energy storage to manage intermittency when employing autonomous renewable sources.

The data presented in Table 8 below is typical for installed plants with capacities of 100m^3/day and above[42]. State-of-the-art RO plants can now routinely produce water at 2kWh/m^3 [Geisler et al, 2001], [MacHarg,a], [Andrews et al, 2001] and [Schneider, 2005], and are claimed to be able to produce water at 1.7kWh/m^3 [Articleclick].

Table 8: Electrical Energy Equivalent to produce desalinated water

Type of Desalination	Specific (electrical equivalent) Energy Consumption (kWh/m^3)
MSF	15.5
MED	6.5
Mechanical Vapour Compression	8 - 14
Reverse Osmosis	4 - 7

2.7.5 Decision

For the purpose of this research, the desalination plant was selected based on what would be employed if conventional electrical power were employed to operate it, which in this case is reverse osmosis due to having the lowest specific power consumption. There are though more extensive criteria that would normally be considered for a decision of this type if the decision to use electrical power had not already been taken, see Appendix B Section 1. 'Desalination Plant Selection' for further detail.

Examples of the relevant criteria include:

- RO plant size
- Feed-water salinity
- Remoteness
- Availability of grid electricity
- Technical infrastructure, and
- The type and potential of the local renewable energy resources available locally

It is far easier, from an engineering perspective, to store surplus heat rather than surplus electricity if intermittent renewable energy supplies are being employed and heat based systems may have been preferable in Massawa once the range of relevant criteria was taken into account. This said, there are issues relating to:

- How water pumping requirements will be met without electrical supplies, and
- The engineering challenges relating to increasing the efficiency of solar energy storage.

[42] It is noteworthy that older and smaller RO systems particularly those that do not employ energy recovery, can easily consume up to 15 kWh/m^3.

3 Types of Renewable Energy to employ

Having decided that renewable energy was to be employed in place of conventional energy to power a reverse osmosis plant, this research investigated the use of renewable energy sources, and whether they could be justified for use without reliance on conventional energy sources, and stand alone as an independent and viable power source in their own right.

The suitability of renewable energy as a viable alternative to conventional energy, for meeting a significant power demand that is fundamental to human need, i.e. the needs of 50,000 people for water at Massawa and Newhaven, was investigated through modelling.

3.1 Overview

All renewable energy sources available to us comes from the sun, apart from geothermal power and tidal energy, which taps into the energy stored as gravitational potential, and kinetic energy, in the Earth/ Moon system.

The following four main types of renewable energy were considered in this research:

- Solar
- Wind
- Tidal current, and
- Wave.

There were other options that could have been employed within this modelling (such as hydro, geothermal, biomass, solar thermal, etc) but they were not investigated further due to time limitations.

3.2 Solar Power

When solar radiation enters the Earth's atmosphere, part of the energy is dispersed by scattering or absorption by air molecules, clouds and particulate matter, usually referred to as aerosols.

Solar radiation can reach the Earth in one or more of three ways to make up the total (global) radiation:

1. The radiation that is not reflected or scattered by aerosol impacts can reach the surface of the Earth directly from the solar source, and is called direct or beam radiation.
2. The radiation that is scattered due to aerosol impacts before it reaches the ground, is called diffuse radiation.
3. Radiation may also reach a receiver after reflection from the ground, and is called the albedo.

3.2.1 Solar radiation that reaches the Earth's surface

The amount of radiation that reaches the ground is extremely variable. In addition to the regular daily and yearly variation due to the motion of the Sun, irregular variations are caused by climatic conditions (cloud cover, etc), as well as by the general composition of the atmosphere. As such, the amount of radiation will vary greatly from one location to another, but on average is taken as 5.74kWh [Markvart, 2002]. Figure 16 below shows the daily solar radiation on a horizontal plane for several locations, ranging from tropical forests to northern Europe. The solar radiation is highest in the continental desert areas around latitude 25° North and 25° South, and falls off towards the Equator due to clouds, and towards the Poles due to low solar elevation. Equatorial regions experience little seasonal variation, in contrast with higher latitudes where the summer/winter ratios of change are large.

Figure 16 below shows the primary energy from sunlight reaching the Earth's surface and it is estimated that each of the disc locations indicated could meet the global power demand [Loster, 2010][43].

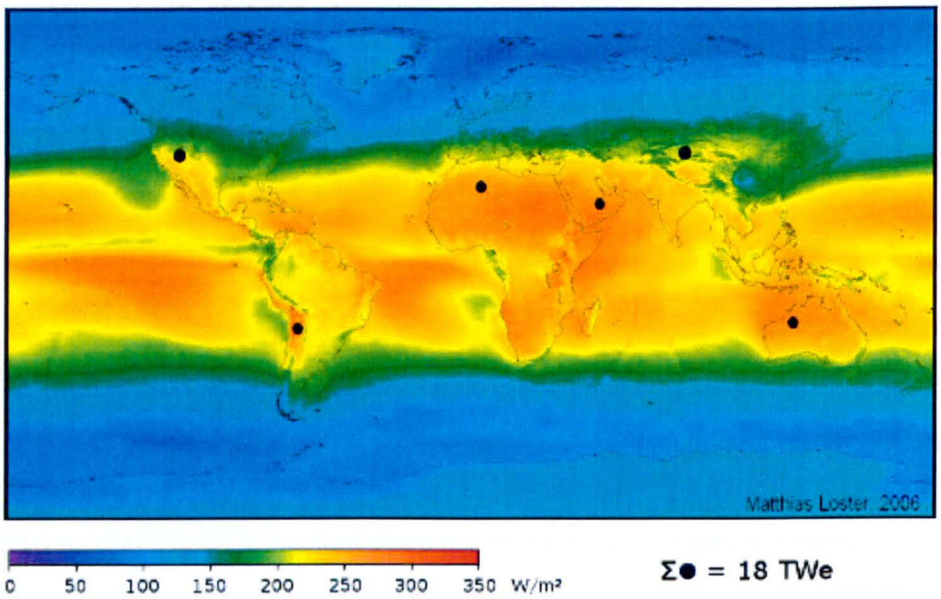

Figure 16: Comparison of locations for solar radiation throughout the year.

3.2.2 Significant quantity of power from solar PV energy.

Solar PV, (which is explained in greater detail at Appendix B), currently generates electricity in well over 100 countries, on an appreciable scale and (according to the Renewables 2010 Global Status Report)

[43] Solar cells, with a conversion efficiency of only 8%, would produce, on average, 18 TW electrical if installed in the desert areas marked by the six discs in the map. Left to Right: USA (Great Basin), South America (Atacama), Africa (Sahara), Middle East (Arabian) and China (Takla Makan). Each of these sites could generate 3TW on average (26,000TWh/y) which equates to around 1/5[th] of global energy consumption of 150,000TWh/y.

[REN21, 2010] maintains its position as the fastest-growing power-generation technology in the world[44]. There are many solar power installations of significant size (over 600 with installed capacity in excess of 2.5MW) and the largest PV plants are in Asia (Charanka in India and Golmud in China generating more than 200MW each. The current installed global solar PV capacity is around 40GW [REN21, 2011].

3.3 Wind

One to two percent of the energy radiated by the sun is converted into wind energy, giving a range of global wind power available from 1750 to 3500TW (15000000 to 31000000TWh/y), which is orders of magnitude more than the current global energy consumption of 150000TWh/y.

The regions around the Equator, at 0° latitude, are heated more by the sun than the rest of the globe, as indicated below in Figure 17 in the warm colours, red, orange and yellow[45].

Hot air rises into the sky until it reaches approximately 10 km (6 miles) altitude, and spreads to the North and the South. If the globe did not rotate, the air would simply arrive at the North Pole and the South Pole, sink down, and return to the Equator.

Since the globe is rotating, any movement on the Northern hemisphere is diverted by a phenomenon known as the Coriolis Effect, which is simply explained in 'Atmosphere, Weather, Climate' [Barry, 2003].

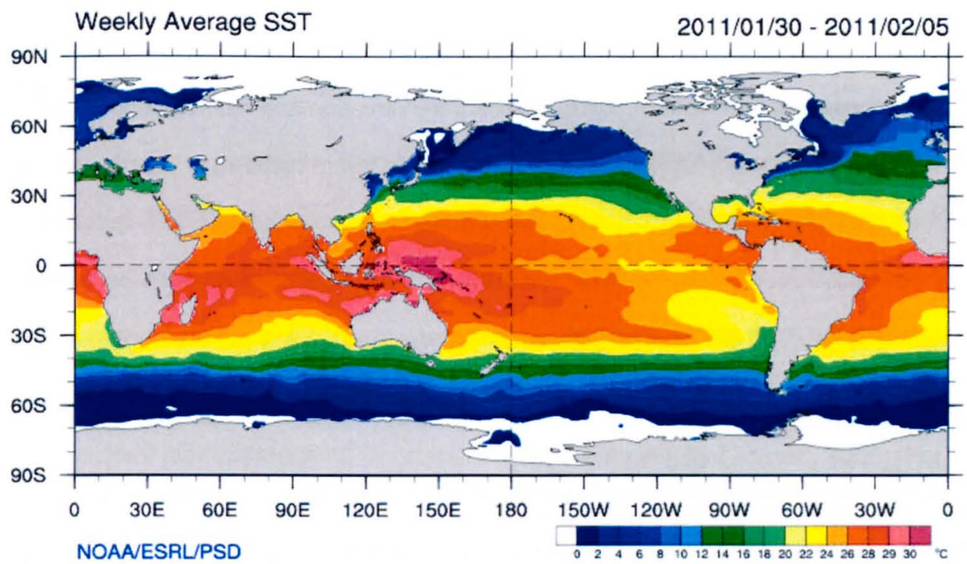

Figure 17: Sea surface temperatures during February 2005 during El Nina

[44] Between 2004 and 2009, grid-connected PV capacity increased at an annual average rate of 60 percent. An estimated 7 GW of grid-tied capacity was added in 2009, increasing the existing total by 53 percent, to some 21 GW (off-grid PV accounts for an additional 3–4GW). This was the largest volume of solar PV ever added in one year, and came despite a precipitous decline in the Spanish market relative to 2008. Solar PV accounted for about 16 percent of all new electric power capacity additions in Europe in 2009.

[45] Taken from Tropical Weather: Weather Underground on 16 October 2010, available at http://www.wunderground.com/tropical/ [Last viewed on 7 August 2011].

3.3.1 Significant quantity of power from wind energy.

New wind power installations in 2009 reached 38 GW, which represents a 41 percent increase over 2008, and brought the global total to 159 GW. China was the largest installer in 2009, representing more than one-third of the world market[46].

There are a significant number of wind farms with in excess of 100MW installed capacity, with the Jaisalmer wind farm in India (rated at 1GW) being the world's largest. Windfarm details for individual countries are available at 'The Wind Power wind turbines and wind farm data base' [The Wind Power]. It is also noteworthy that the UK Walney wind farm in Kent is currently the largest offshore facility in the world rated at 367MW and there is currently almost 240GW of wind power installed around the world [Hill, 2011].

3.4 Marine current

There are two main types of marine current:

- Non-tidal currents, and
- Tidal currents

3.4.1 Non-Tidal Currents

The fastest oceanic non-tidal currents are derived by a complex process involving the adsorption of solar radiation in the ocean and atmosphere, followed by a transformation and redistribution from the Equator towards the Poles by moving currents of air and water, and finally, a focusing of the oceanic currents on the western edges of ocean basins (or the eastern coasts of continents) by the Earth's rotation.

The Gulf Stream in the Atlantic, the Kuroshio off Japan, and the Agulhas-Somali system on the East African coast, form the main current systems.

3.4.2 Tidal Currents

Tidal currents are the consequent flow of ocean water due the rise and fall of tides. Other factors, such as salinity and local temperature differences, also make a contribution to the movement of ocean water. This can be magnified by underwater topography, particularly in the vicinity of land, or in straits between islands and mainlands.

[46] As an indication of the speed of development in the last six years, China accounted for only about 2 percent of the global market in 2004, and wind power capacity surpassed the country's installed nuclear capacity in 2009, with just over 13.8 GW added to reach a total of 25.8 GW. China doubled its existing wind power capacity for the fifth year running, in 2009.

The tides are generated by the rotation of the Earth within the gravitational fields of the moon and sun. The relative motions of these bodies cause the surface of the oceans to be raised and lowered periodically, according to a number of interacting cycles:

A **half-day (semi-diurnal) cycle**, results in a period of 12 hours 25 minutes between successive high waters.

Daily (diurnal) tides occur in some regions, such as the Gulf of Mexico. These have only one high tide and one low tide in a 24-hour period.

A **14-day cycle**, resulting from the superposition of the gravitational fields of the moon and sun. At new moon and full moon, the sun's gravitational field reinforces that of the moon, resulting in maximum tides or *spring tides*. At quarter phases of the moon, there is no reinforcement, resulting in minimum or *neap tides*. The range of height of a spring tide is typically about twice that of a neap tide.

The tides create movements of water into and out of bays and estuaries. These movements can create currents, significant tidal ranges, or both.

The processes by which these currents are formed, depend on the local topography and vary widely. The currents created by the movements are known as **tidal streams** or **marine currents**.

3.4.3 Power of ocean currents available

The total global power of ocean currents is estimated to be about 5TW [Issacs and Seymor, 1973] (44000TWh/y), which is of the same order as current global electricity consumption at 150000TWh/y, but this ocean current estimate is debated by [Frõberg, 2006]. However, energy extraction is practical only in a few areas where the currents are concentrated near the periphery of the oceans, or through straits and narrow passages between islands and other landforms.

The power of a current is proportional to the cube of the current velocity [Cornett, 2009]. For tidal currents close to the shoreline in estuaries, and in channels between mainland and islands, the velocity varies sinusoidally with time, with a period relating to the different tidal components.

3.4.4 Quantity of power from tidal current energy.

The first significant tidal current installation was the 240MW La Rance tidal barrage in France, which began generating power in 1966. Today, there are a few modern commercial projects generating power, and numerous other projects are in development or under contract [Brito-Melo and Huckerby, 2008]. An estimated 6MW system is operational or being tested in European waters (off the coasts of Denmark, Italy, the Netherlands, Norway, Spain, and the United Kingdom), with additional projects off the shores of Canada, India, Japan, South Korea, the United States and elsewhere. At least 25 countries are involved in ocean energy development activities.

During 2009, South Korea completed a 1MW tidal-current plant and began construction of a 260 MW tidal plant. Further, the Jindo Uldolmok Tidal Power Plant is planned to be expanded progressively to 90 MW of capacity by 2013. The Jiangxia Tidal Power Station near the mouth of the Yalu River in China is operational, with current installed capacity of 3.2MW.

The first tidal power site in North America was the Annapolis Royal Generating Station opened in 1984, on an inlet of the Bay of Fundy. It has 18MW installed capacity, and the first in-stream tidal current generator in North America was installed at Race Rocks on southern Vancouver Island in September 2006.

A small project was built by the Soviet Union at Kislaya Guba on the Barents Sea with 0.4 MW installed capacity.

Europe has added at least 0.4 MW of ocean power capacity. The United Kingdom is currently at the forefront, with 1.5 MW of tidal stream capacity, and a 1.2 MW tidal current plant—the world's first commercial-scale tidal turbine to generate electricity for the grid, producing enough to power about 1,000 homes.

3.5 Wave energy

Wave energy can be considered a concentrated form of solar energy. Winds are generated by the differential heating of the Earth, and as they blow over large areas of water, part of their energy is converted to waves. The amount of energy transferred, and the size of the resulting waves, depends on:

- The wind speed
- The length of time for which the wind blows, and
- The distance over which it blows (the 'fetch').

Solar power levels of typically 100 W/m^2, can be converted to waves with power levels of 10-50 kW/m of wave crest length, (the standard form of measurement). Within or close-to the generation area, storm waves known as the 'wind sea', exhibit a very irregular pattern, and continue to travel in the direction of their formation, even after the wind turns or dies down. In deep water, waves can travel out of the storm areas with a minimal loss of energy, and progressively become regular, smooth waves or a 'swell', which can persist for great distances (i.e. tens of thousands of kilometres) from the origin.

Consequently, coasts with exposure to the prevailing wind direction and long fetches, tend to have the most energetic wave climates—e.g. the western coasts of the Americas, Europe and Australia/New Zealand, as shown in Figure 18 below with approximate lines of latitude included [DTI, 2003].

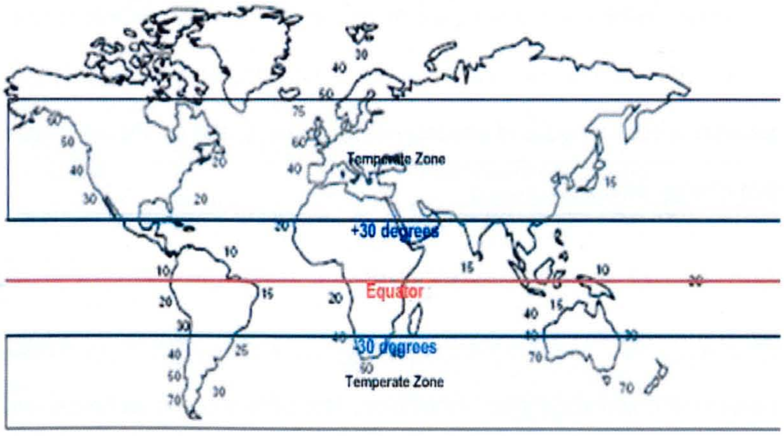

Figure 18: Global distribution of offshore annual wave power level in kW/m wave crest

3.5.1 The global wave potential

According to [Renewable UK], the global wave power potential has been estimated to be 8700-87000TWh/y (1-10 TW), which is (as with tidal current) of the same order of magnitude as world electrical energy consumption at 150000TWh/y. Figure 18 above shows that the best wave climates, with annual average power levels between 20-70 kW/m or higher, are found in the temperate zones (between 30 and 60 degrees latitude) where strong storms occur. However, attractive wave climates are still found within ±30 degrees latitude where regular trade winds blow; the lower power levels being compensated for by the reduced wave power variability.

3.5.2 The power available from waves

The power available is proportional to the square of the wave height, and to the wave period. There are great variations in power levels with the passage of each wave, from day to day, and from month to month. However, the seasonal variation is generally favourable in temperate zones, since wave energy is at its greatest in the winter months, coinciding with the greatest energy demand [Cru, 2008].

3.5.2.1 Offshore wave resource

As waves approach shorelines, they can be modified in several ways, leading to changes in direction (due to refraction) and power (due to losses arising from seabed friction and wave breaking). Refraction may cause re-focusing and wave energy concentration ('hot spots') over a convex seabed, and this behaviour is relatively common in the vicinity of headlands. The opposite effect (defocusing and energy refraction over a concave bottom) may occur in bay areas. The energy losses depend on the width of the continental shelf and the steepness and roughness of the seabed, and can reach values of about half the offshore wave power level.

3.5.2.2 Shoreline wave resource

The shoreline wave energy resource is even lower than the near-shore resource, because of further energy dissipation mechanisms. For a variety of reasons, including unsuitable geomorphologic conditions at the shoreline, excessive tidal range and environmental impacts, not all shoreline sites are suitable for deployment of wave energy devices.

3.5.3 Quantity of power from wave energy.

A 2.5MW commercial wave plant was installed in Portuguese waters in 2008, as stated in the [Pelamis Wave Power] but was shut down soon after installation. The details of the technical and financial troubles associated with this shutdown are included at the latter part of 'Pelamis Wave Power Jettisons Its CEO, Rough Waters Ahead?' [Kanellos, 2009].

3.6 Conclusion

The types of renewable energy (solar PV, tidal current, wind and wave) considered within this research all have the potential to produce enough power to meet a significant proportion of current power demands, if not all of it. This potential for power production has been realised on the MW scale in all cases except for wave power, which is still at a relatively early stage of development.
There is however little evidence to indicate that any of these renewable energy sources are currently employed to address a fundamental human need on a significant scale, i.e. to provide a resource that is essential for continued human habitation of that area.

3.7 Reverse osmosis installations using renewable energy.

There are a number of reverse osmosis installations around the world using renewable energy to produce water.
The following sections provide detail of renewable energy-powered RO plants
These are considered in terms of their:

- Degree of reliance on renewable power, and
- Use to meet the fundamental need for drinking water.

The renewable energy employed is predominantly wind or solar power, and a précis of the installations around the world is presented below in Table 9 and Table 10 respectively [PRODES, 2010].

Note: The data is incomplete and for ease of presentation, the Tables are simplified versions of the original data.

Table 9: Global Wind Powered Reverse Osmosis Plants

Location	Capacity(m^3/day)	Wind power installed.	Year Commissioned
Canada	10		1974
Island of Suderoog at the German Coast of the North Sea	6 - 9	6kW	1980
Ile du Planier (near Marseilles), France	12	4kW	1982
MarsaMatrouh, Egypt	25		1987
Island of St.Nicolas, West France		10kW Wind Energy Converter, Diesel Generator	1988
Western Australia	~ 0.2	Wind Energy Converter, 42kW PV, Diesel Generator	1988
Island of Drenec, France		10kW	1990
Perth, Australia	0.15-0.3		1990
Pozolzquierdo, Gran Canaria island, Spain	96	6.6kW	1996
Therasia Island, Greece	4.8	15kW	1997
Maagan Michael, South of Haifa, Israel	9.6	0.6kW Wind Energy Converter, 3.5kW Photovoltaic Generator, 3kW Diesel Generator	1997
Pozolzquierdo, Gran Canaria island	15	Vergnet, 15kW	1999
Gran Canaria , Spain	2712 – 4000	Wind energy	2001
Lavrio, Attiki, Greece	3.6	3.96 PV, 1 kW Wind Energy Converter	2001
Agricultural Univ. of Athens (AUA), Greece	1.5-3	850W PV, 1kW Wind Energy Converter	2001
U.K.	10	2kW	2002
Perth, Australia	144000	82MW	2006
Heraklia Island, Greece	80	30kW offshore wind, battery bank,	2007
Delft University, The Netherlands	5-10	Commercial wind mill	2007/8
Gran Canaria	10	15kW Wind Generator, mechanical coupling to RO	
Gran Canaria	15	15kW Wind Generator, hydraulic coupling to RO	

Table 10: Global Solar Powered Reverse Osmosis Plants

Location	Capacity (m^3/day)	Solar power installed.	Year Commissioned
Conception del Ore, Mexico	0.71	2.5kW	1978
La Luz, Mexico	15	5kW	1979
Giza, Egypt	5-7	7kW	1980
Jeddah, Saudi Arabia, near the Red Sea	3.25	8kW	1980
Cituis West Java, Indonesia	36	25kW	1982
Perth, Australia	2.4	1.2kW	1982
Okikawa, Japan	15		1982
Las Barrancas, Mexico	24		1982
Qatar	24		1982
Wanoo Roadhouse, Australia		6kW	1982-83
Vancouver, Canada	0.5-1	4.8kW	Around 1983-84
Doha, Qatar	5.7	11.2kW	Possibly around 1984
Del Ore, Mexico	2		1984
Sant Nicola, Italy	12		1984
Canada	2		1984
Canada	3		1984
Tanote in Thar Desert, Rajasthan state, India	1-2	0.45kW Photovoltaic Generator, Diesel Generator	1986
Ohsima Island, Funke City, Nagasaki	10	25kW	1986
Hiroshima, Japan	20		1987
Brountsville, Texas, USA	36	Solar energy, Fresnel lenses	1987
Hassi-Khebi, Algeria	22.8	2.59kW	1988
University of Almeria, Spain	2.5	23.5kW	1988
Yanbu, Saudi Arabia	20		1988
Sulaibiya, Kuwait	45		1988

Location	Capacity (m^3/day)	Solar power installed.	Year Commissioned
Western Australia	~ 0.2	Wind Energy Converter, 42kW PV, Diesel Generator	1988
Marett island, Italy	5		1989
Lipari Island, Italy	48	63kW	1991
Punta Libeccio, Marettimo Island, (north west of Sicily), Italy		9.8kW Photovoltaic Generator, 30 kW Diesel Generator	1993
Sadous Riyadh Region, Saudi Arabia	14.4	10.89kW	1994
Florida St. Lucie Inlet State Park, U.S.A.	0.6 (2´ 0.3)	2.7kW Photovoltaic Generator, Diesel Generator	1995
Colorado, USA	2.8	2.3kW	1995
Gillen Bore, Australia	1.2	4.16kW	1996
Maagan Michael, South of Haifa, Israel	0.4	0.6kW Wind Energy Converter, 3.5kW Photovoltaic Generator, 3 kW Diesel Generator	1997
Pozolzquierdo, Gran Canaria island	30	6.6kW	1998
Germany	0.2-20	Solar collectors, PV for pumping needs	1999
Coite-Pedreiras, Brazil	6	1.1kW Photovoltaics, Diesel Generator	2000
INETI Portugal	12	50-100W	2000
Sadous Village, Saudi Arabia	14.4	10.08kW	2001
Lavrio, Attiki, Greece	3.6	3.96kW PV, 1kW Wind Energy Converter	2001
Agricultural Univ. of Athens (AUA), Greece	1.5-3	850W PV, 1kW Wind Energy Converter	2001
U.K.	3	2.4kW	2001-2002
Bahrain	1.5	1.32kW	2002
White Cliffs, New South Wales, Australia	0.5	150W	2003
Mesquite, Nevada	3.26	~ 400W	2003
KsarGhilène (Tunisia)	50.4	10.5kW	2006
AitBenhssaine village, rural commune Tamaguerte in the Alhaouz Province, Morocco	24	4.8kW	2008
Msaim Village, Had Dra Commune, in the Essaouira province, Morocco	24	3.9kW	2008
Municipality of Amellou, Province of Tiznit, Morocco	24	4kW	2008
Municipality of Tangarfa, Province of Tiznit, Morocco	12	2.5kW	2008
Municipality of Tangarfa, Province of Tiznit, Morocco	24	4kW	2008
Municipality of Sidi Ahmed Esayeh, Province of Essaouira, Morocco	24	4kW	2008
Pozolzquierdo, Gran Canaria Island, Spain	96	6.6kW	2008
Primary School, Oludeniz District in the Fethiye Region, Turkey	6.9	2.88kW	2008
Hotel in the Fethiye Region, Turkey	2	2.88kW	2009
Hartha Village, Jordan	2.4	0.43kW	2008
HamamLif, Tunisia	0.05	590W	

The accumulation of wind and solar powered reverse osmosis plant capacity is shown below, on a year-by-year basis, in Figure 19 and Figure 20 respectively.

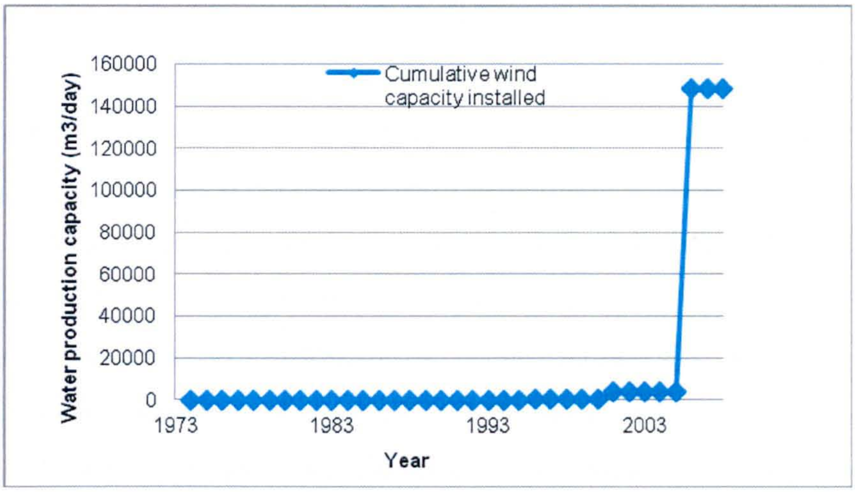

Figure 19: Cumulative global wind powered reverse osmosis capacity (m^3/day)

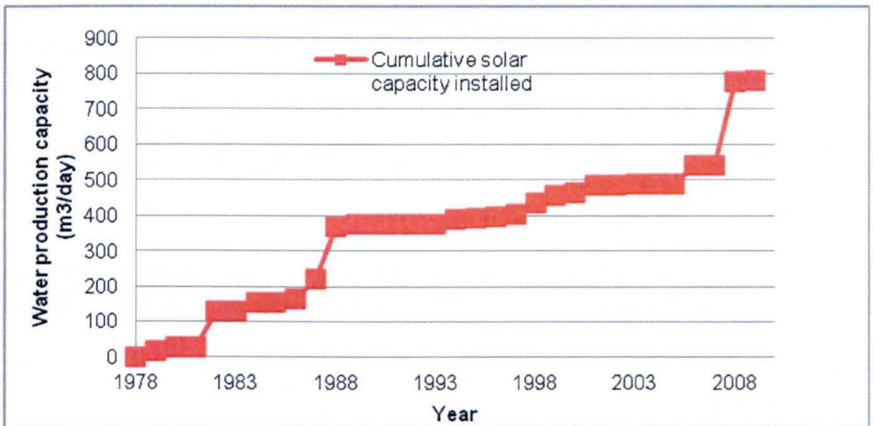

Figure 20: Cumulative global solar powered reverse osmosis capacity (m^3/day)

As can be seen from Figure 19 and Figure 20 above, although there are more solar powered reverse osmosis installations than wind powered (as shown in Table 9 and Table 10), there is significantly more wind powered reverse osmosis capacity than solar.

This is due to two major installations:

- The Seawater Reverse Osmosis (SWRO) plant in Gran Canaria (built in 2001), and
- The Perth SWRO Plant (built in 2006).

The following sections provide detail of these two renewable powered SWRO plants and specifically their:

- Degree of reliance on renewable power, and/ or
- Use to meet the fundamental need for drinking water.

3.7.1 The Seawater Reverse Osmosis (SWRO) plant in Gran Canaria Canary Islands.

This reverse osmosis plant achieves a specific energy consumption of less than 2.9 kWh/m^3 of produced water, over the whole process[47], and has a water production capacity of just over $4000m^3/day$.

The main source of energy powering this RO plant is a farm of 4 wind generators, while the main use for the water produced, is irrigation of tomato and vegetable fields with an area of 2,300 hectares.

Rainfall is very low in the Canary Islands, typically less than 250 mm as an annual average. The sources of fresh-water are therefore very limited and SWRO desalination was considered the only option in order to meet the growing demand for water. Local water demand is currently increasing at around 6% per year.

Shown below in Table 11 is the operational performance of the wind generators (4x Gamesa G47 – 660kW Turbines) supplying power to the SWRO plant in Gran Canaria which clearly shows that the total power required by the Seawater Reverse Osmosis plant (shown in '**bold**') is less than 50% of the installed wind farm capacity. When the output from the wind generators is not sufficient, the SWRO is powered by energy from the network [Vodmar et al, 2005].

Table 11: Wind Generator performance at the Seawater Reverse Osmosis (SWRO) Plant in Gran Canaria

Operational Year	2003	2004
Power produced by Wind Turbines ($kWh x10^6$)	10.21	9.64
SWRO Power Consumption from Wind Turbines ($kWh x10^6$)	1.55	2.40
SWRO Power Consumption from Grid ($kWh x10^6$)	0.68	1.80
Power sold to the Grid ($kWh x10^6$)		7.24
Total SWRO Power consumption ($kWh x10^6$)	**2.23**	**4.20**
Total Annual Permeate Production ($m^3 x10^6$)	0.76	1.47

3.7.2 The Perth Seawater Reverse Osmosis (SWRO) Plant at Kwinana

Electricity for the Perth SWRO plant is purchased from the 80MW Emu Downs Wind Farm, which offsets its use of conventional power. The RO plant has an overall 24MW power requirement, and a production demand of $4.0kWh/m^3$ to $6.0kWh/ m^3$, achieved using pressure exchanger technology. The pressure exchanger methodology is explained in greater detail at Appendix B.

The farm itself consists of 48 Vestas wind turbines (each with 1.65 MW generating capacity) located 30km east of Cervantes, some 200miles outside Perth. It contributes 270 GWh/year into the general power grid, offsetting the 180 GWh/year requirement from the desalination plant.

The SWRO plant is explained in detail in Australia's first big plant thinks "green" [Crisp, 2006], but concisely has an initial daily capacity of $140,000m^3$, with designed expansion up to $250,000m^3/day$. The plant is the largest single contributor to the area's integrated water supply scheme, and it is estimated

[47] The innovative design employs energy recovery using pressure exchangers, as well as motors with frequency control.

that this will meet around 17% of the water needs for Perth. The Perth SWRO plant is also the largest of its kind in the southern hemisphere and the biggest in the world to be powered using renewable energy.

3.8 Conclusion

It is noteworthy that both of these RO plants, which are the only two in existence that produce a significant amount of water based on renewable energy:

- Rely on the electricity grid to operate, and use renewable energy to offset, and
- Produce water that is not the sole supply to the local users.

The literature reveals that while there are several reverse osmosis desalination plants that use renewable energy, there are none that totally rely upon it as their single source of potable water. As such, the research and findings described in this thesis, for the production of a single source of water using only renewable energy, for a population of 50,000 are considered novel.

4 Modelling

The objective of the modelling exercise was to calculate the amount of water delivered by renewable energy powered RO plant scenarios in comparison with the same RO plant operated continuously using conventional, non-intermittent power sources.

The rest of this Chapter will:

- Provide an overview of how an RO plant works
- Describe the stages of modelling data derivation employed in this research, and
- Describe the modelling exercise itself.

Greater detail of the modelling undertaken for this research is available in Appendix B.

4.1 How an RO plant works

Reverse osmosis is a form of filtration, in which the filter is a semi-permeable membrane that allows water to pass through, but not salt. When a membrane of this type has saltwater on one side and freshwater on the other, and no other forces are acting, water will flow through the membrane towards the saltwater side, reducing the difference in salt concentration. This is the natural process of osmosis, which is widely employed in the cells of all living species. In reverse osmosis desalination, the aim is to increase the quantity of freshwater, and so a pump is employed to make the flow reverse, hence the name: reverse osmosis.

The osmotic pressure of typical seawater is around 26bar, and this is the pressure that the pump must overcome in order to reverse the natural osmotic flow. Twenty-six bar also equates to the theoretical minimum energy consumption of 0.7kWh/m^3 [Lachish, 2003], but in practice, a significantly higher pressure is used in order to achieve a generous flow of freshwater, known as the 'permeate'.

As freshwater passes through the membrane, the remaining saltwater becomes more concentrated and, for the process to continue, this concentrate, known as brine, must be continuously replaced by new feed water. To achieve this, the feed water is pumped across the membrane as well as through it; hence, RO is a cross-flow filtration process as depicted in Figure 21 below.

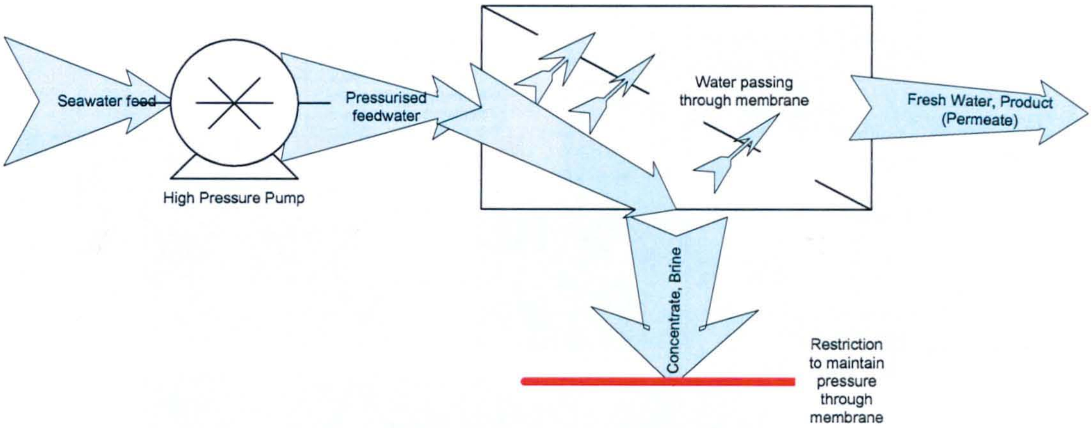

Figure 21: Reverse Osmosis filtration process

As can be seen from Figure 21, a proportion of the pressurised feedwater comes out of the reverse osmosis module as waste or concentrate/ brine. This concentrate or brine is at a pressure only slightly below that of the feedwater, meaning that it contains a significant amount of the hydraulic power originally supplied by the pump.

This energy can be partially recovered, dramatically improving the overall system efficiency. This is known as brine-stream recovery (BSR) and is described in more detail at section 4.3.2.1 and section 4.3.2.2 for Pelton Wheel and Pressure Exchanger variants, respectively.

4.2 The stages of modelling

The six main modelling data derivation stages were:

1. No BSR Plant Design
2. Model of primary renewable energy source, and Stage 1, its application to No BSR RO Plant.
3. Design of BSR RO plants
4. Stage 2, the application of primary renewable energy source to BSR RO plants
5. Design of supplementary renewable energy sources and, Stage 3, application to BSR and No BSR RO Plants, and
6. Design of model for hydrogen storage and re-use, Stage 4.

The derivation of the data used in the modelling for this research is presented as Appendix B, which also provides background detail to the modelling exercise section below.

Figure 22 and Figure 23 below show:

- The modelling data derivation stages for the No BSR and BSR RO plants, respectively, and
- The modelling exercise stages that were applied to each, which are explained in more detail in 'The Modelling Exercise' at section 4.3 below.

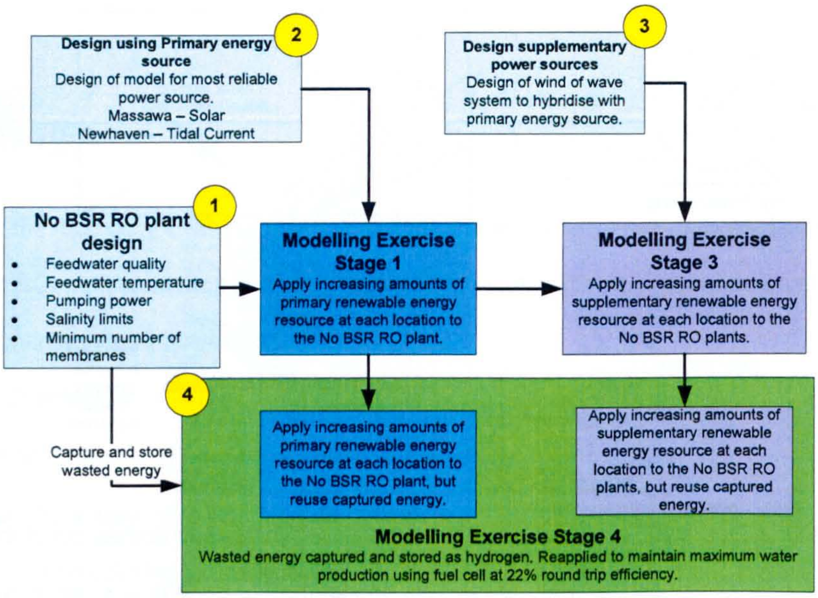

Figure 22: No BSR RO plant modelling process

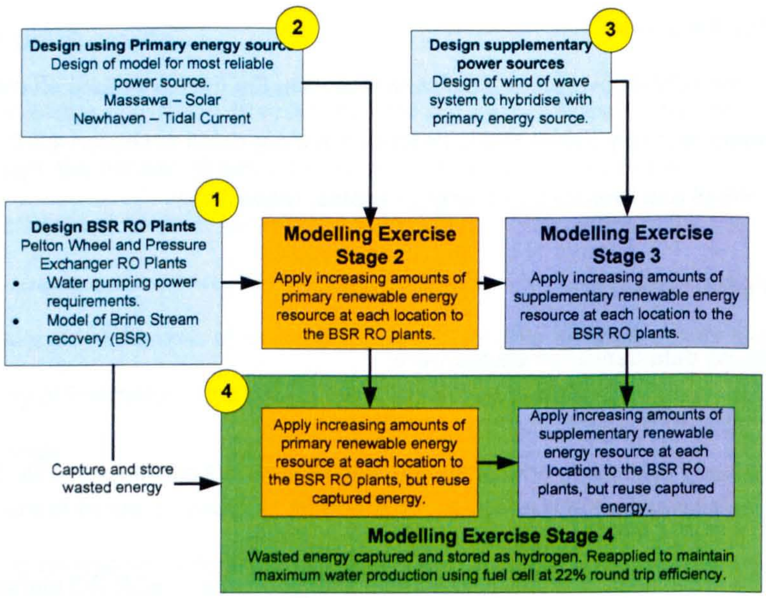

Figure 23: BSR RO Plant modelling process

4.3 The modelling exercise

The modelling exercise was conducted in four main stages using a range of scenarios to simulate varying amounts and types of renewable power being applied to various RO plants as shown below in Figure 24.

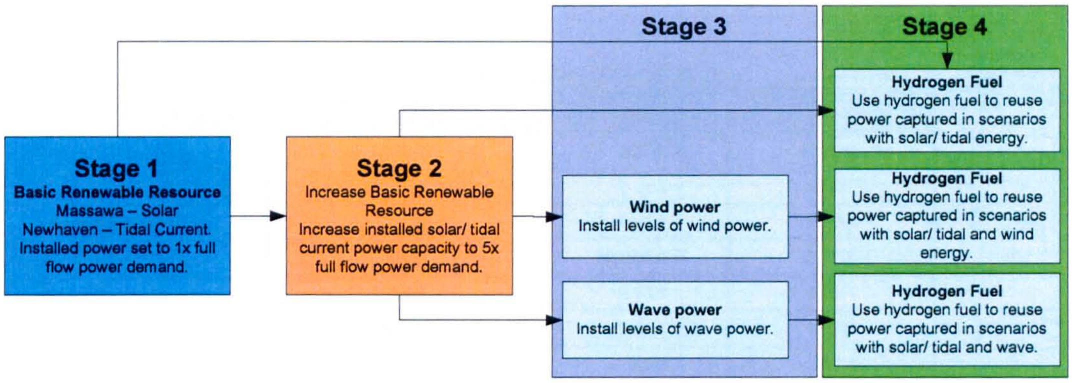

Figure 24: Four stages of the modelling exercise

The four stages of model development are explained in the following text.

4.3.1 Stage 1

Stage 1 employed the most reliable renewable resource at each of the sites in question (Solar at Massawa, and Tidal Current at Newhaven) as shown below in Figure 25 with the No Brine Stream Recovery (BSR) RO plant only.

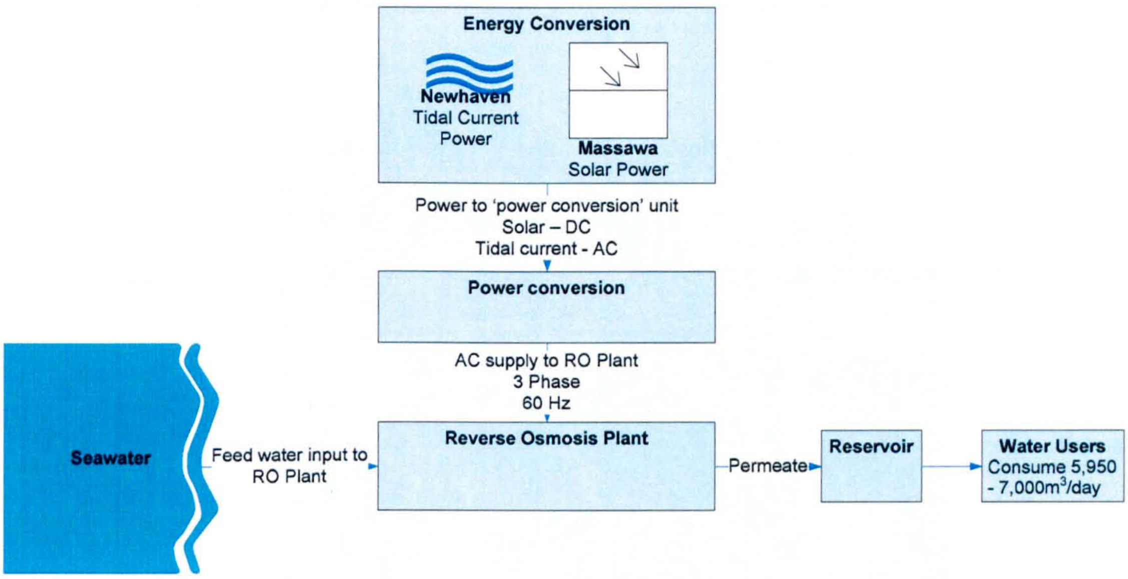

Figure 25: Single source of renewable energy to power RO plant at both sites.

The No BSR RO plant employed within this research is shown below in Figure 26.

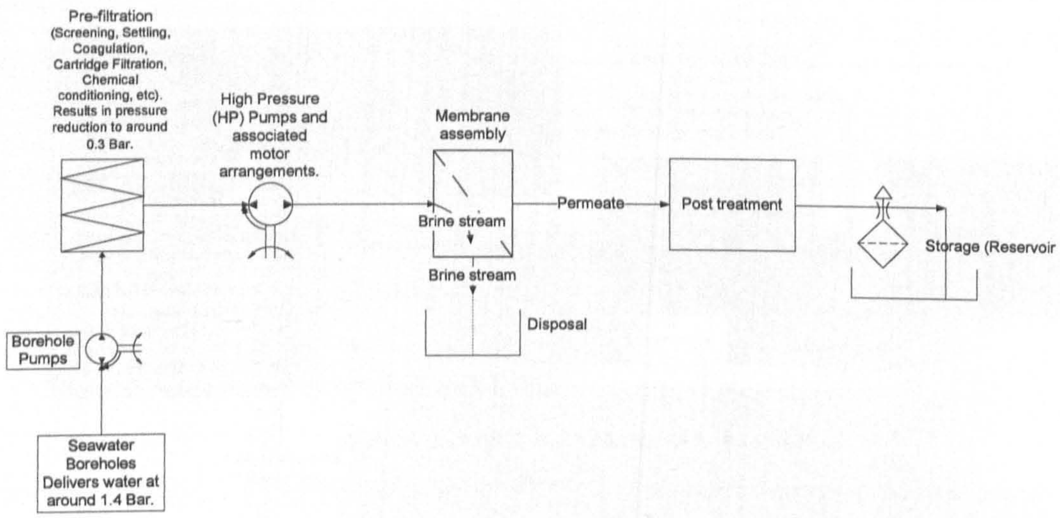

Figure 26: No BSR Plant type used within modelling.

Sufficient power was installed at each site so that the maximum power output during the year from the renewable power source would achieve the maximum flowrate of the RO plant. Additional power was then added in discrete levels, up to (and including) five times the power needed to achieve the maximum flowrate of the RO plant. The additional power capacity would extend the period for which the RO plant could be operated at or near peak output.

4.3.1.1 Levels of Solar power modelled.

HOMER (energy modelling software for renewable energy systems)[48] was employed to derive the solar irradiance on an hour-by-hour basis at Massawa based on the monthly averages shown below in Table 12.

[48] The HOMER energy modelling software is used for designing and analysing hybrid power systems, and is available at http://homerenergy.com/ [Last viewed on 7 August 2011].

Table 12: Average monthly irradiance

Month	Original monthly average (W/m^2/day during that day)	Conversion to kWh/m^2/day[49]	Clearness index[50] applied by HOMER
Jan	303	7.272	0.895
Feb	357	8.568	0.954
Mar	366	8.784	0.884
Apr	376	9.024	0.855
May	337	8.088	0.754
Jun	306	7.344	0.686
Jul	300	7.2	0.674
Aug	301	7.224	0.684
Sep	330	7.92	0.784
Oct	319	7.656	0.830
Nov	308	7.392	0.891
Dec	295	7.08	0.905

Table 13 above shows the original data for Massawa [Thomson, 2003a], which was converted into a format suitable for HOMER, which when inputted into HOMER generated the:

- Appropriate 'clearness index' to be applied, and
- An hour-by-hour irradiance profile in terms of W/m^2, which is shown below[51] in Figure 27.

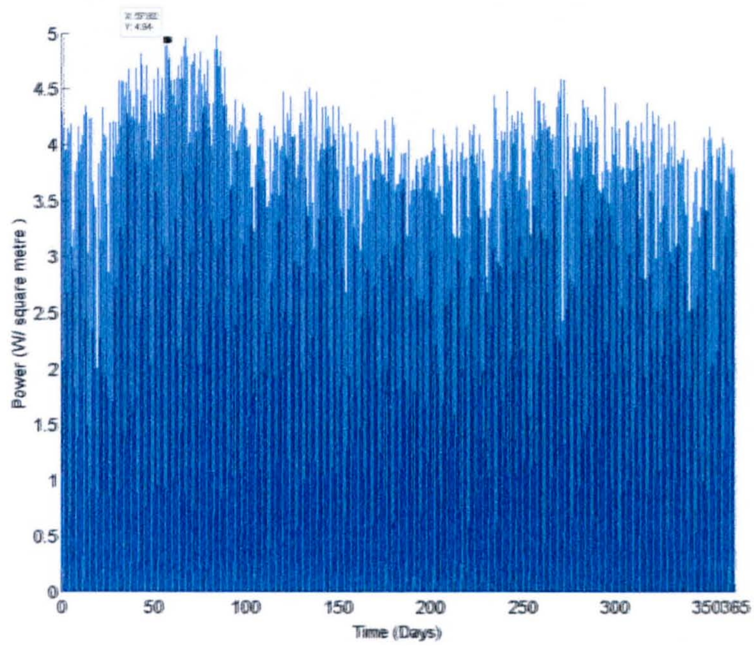

Figure 27: Hourly irradiance at Massawa over one year

---

[49] The original monthly average irradiance, which was presented in W/m^2/day, was converted to kWh/m^2/day as these were the units required to input the data to HOMER.

[50] The 'clearness index' is a dimensionless number between 0 and 1 indicating the fraction of the solar radiation at the top of the atmosphere that is able to pass through the atmosphere to the Earth's surface. Greater detail of its derivation within HOMER is available within the 'Help' pages of HOMER.

[51] This was based on setting for East Africa (GMT +3hr) 15º 36' 33"N. 39º 26' 43"E.

As can be seen from Figure 27 above, the maximum irradiance during the year was 4.9403W/m^2 at 57.62 days[52].

4.3.1.1.1 *Rated installed capacity*

The installed solar power required was based on the Sharp 235W Solar Panel, Monocrystalline, Clear, NU-U235F1, which is rated at 235W, measured at Standard Test Conditions[53], from a panel of 994mm x 1640mm. This panel is quoted as 14.4% efficient, but for this model is only credited with 10% efficiency to account for synchronisation and ambient temperature losses [Sharp, 2009].

The power required at each solar power capacity modelled for the No BSR RO plant, and the corresponding area of solar PV panels that were required to achieve it, are shown below in Table 13.

Table 13: Increments of solar power modelled

Multiple of maximum flowrate	Non-Intermittent Power Required (MW)	Area of solar panels installed (based on 10% efficiency). (m^2)	Area in square (km^2)	Rated installed capacity, based on 1.44W max/m^2 Units (MW)
1	2.4	4857950[54]	4.86	7
2	4.8	9715900	9.72	14
3	7.2	14573850	14.57	21
4	9.6	19431800	19.43	28
5	12.0	24289750	24.29	35

The power settings were modelled and the results are presented at section 5.1.

4.3.1.2 Modelling of Tidal Current Power

It was decided that the tidal current device that would be modelled would be as technically proven as possible and available to be installed now, so from the multitude of tidal device options available, the SeaGen Turbine[55] device was selected for use in this research and is shown below in Figure 28.

---

[52] On closer later inspection, two higher values, of 4.962W/m^2 at 57.625 days and 4.979W/m^2 at 84.625 days, were identified. These higher values were not used to recalculate the results as the potential impact was considered negligible.

[53] Standard Test Conditions: Temperature 25°C, 1 kW/m^2 insolation, Air Mass Coefficient (AM) 1.5.

[54] Maximum flow rate power equates to maximum solar power achieved during year = 4.940356W/m^2, so divide by 1000m to convert figure to kW gives 4.94×10^{-3}kW/m^2. 2,400kW/ 4.94×10^{-3}kW/m^2= 485795m^2. But this assumes 100% efficiency, so 4857950m^2 (4.86km^2) required to achieve power levels quoted at 10% conversion efficiency.

[55] By using twin rotors, Marine Current Turbines estimate that the SeaGen can achieve double the power, for only 60% extra cost over a single turbine. Blades would only travel at a maximum of 12-15 m/s, which is taken to be slow enough so as not pose a danger to marine life.
A working example of a 1.2MW SeaGen tidal energy system was installed by Marine Current Turbines Ltd (MCT) in Strangford Lough in April 2008.

Figure 28: Marine Current Turbines Limited SeaGen Turbine

4.3.1.2.1 Model of SeaGen Operation

The SeaGen Turbine's power output in relation to the prevailing tidal current speed was approximated using a fifth order polynomial which is shown on the graph in Figure 29 below.

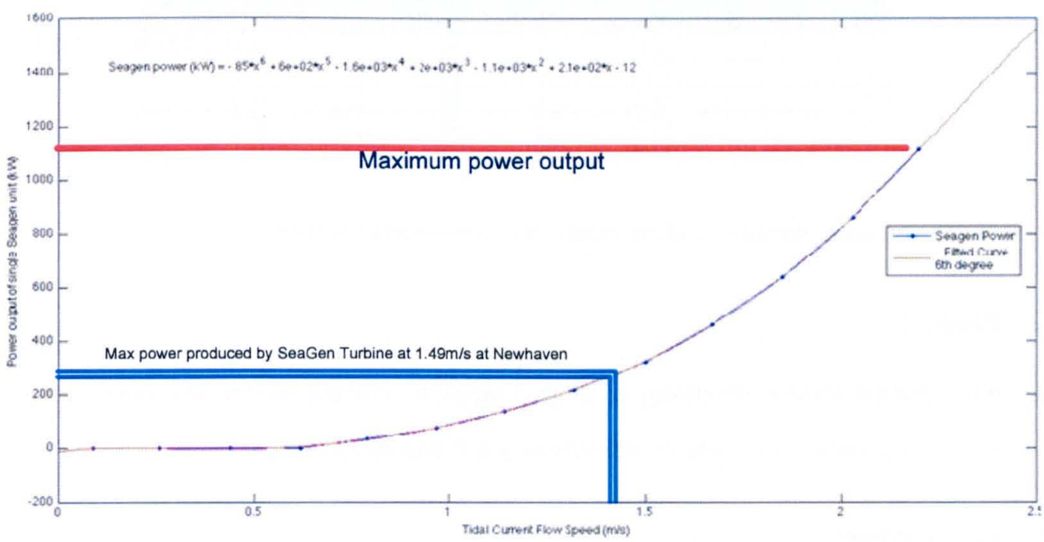

Figure 29: Power output of single SeaGen Turbine

It is noteworthy (as can be seen from Figure 29 above) that due to the limited tidal current speeds at Newhaven, the SeaGen Turbine is (at best) not expected to achieve more than 1/3rd of its rated capacity during the year. This polynomial was applied to the tidal current speeds derived for Newhaven resulting in the power output from a single 1,113kW over the course of one year, shown below as Figure 30.

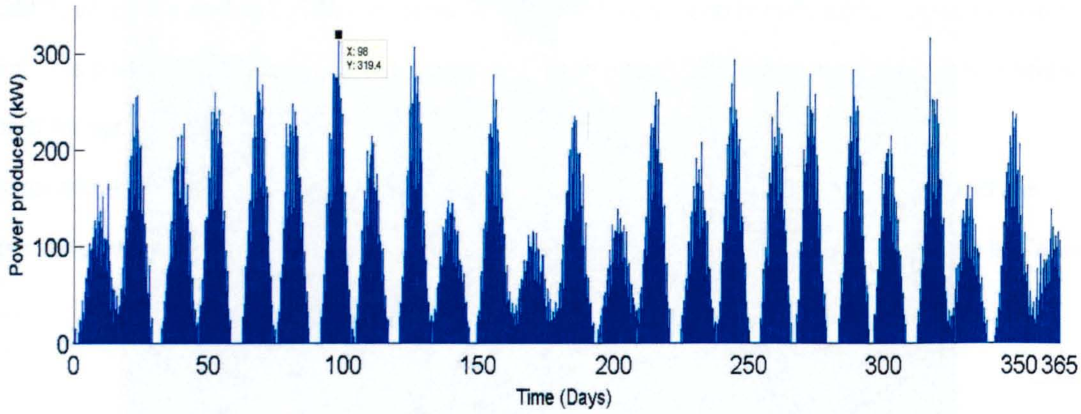

Figure 30: Power output from single SeaGen Turbine at Newhaven over 1 year (kW)

There are many new tidal devices which claim to be able to work better at lower water speeds, such as 'Deep Green' [Minesto, 2012], but they are currently not as developed as SeaGen and were not considered viable for implementation now.

The power required at each tidal current power capacity modelled for the No BSR RO plant and the corresponding number of SeaGen Turbine units that are required to achieve it are tabulated below in Table 14.

Table 14: Increments of Tidal Current Power modelled at Newhaven

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of SeaGen Units required	Tidal current capacity installed (MW)
1	3.4	10	11.1
2	6.8	20	22.3
3	10.2	30	33.4
4	13.6	40	44.5
5	17.0	50	55.7

The power settings were modelled and the results are presented at section 5.1.

4.3.2 **Stage 2**

Stage 2 employed the same methodology as Stage 1 (application of the most reliable power source at each site), but for the BSR RO plants (Pelton Wheel and Pressure Exchanger).

4.3.2.1 Pelton Wheel

The Pelton Wheel RO plant system modelled is shown below in Figure 31.

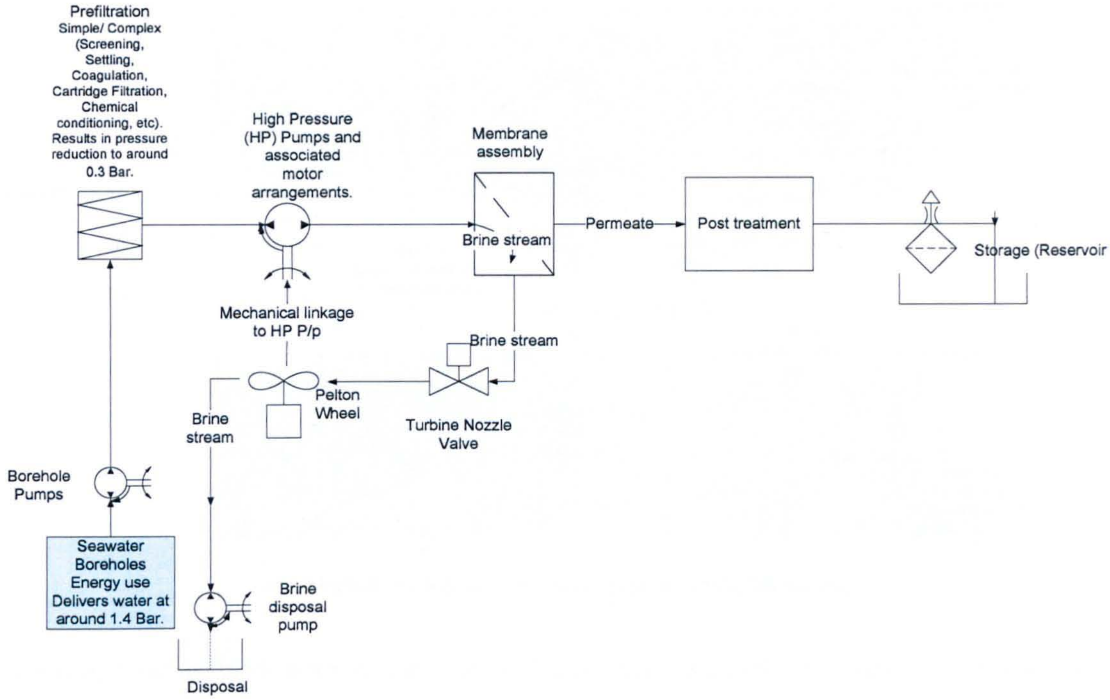

Figure 31: Simple plant using Pelton wheel for BSR design.

As shown in Figure 31 above, the Pelton Wheel BSR RO plant design utilises the brine/ concentrate stream to power a Pelton Wheel turbine, which is mechanically linked to a high pressure pump (HP p/p) arrangement. The power produced from the Pelton Wheel is used to partially pressurise the incoming feedwater, which reduces the external power required to raise the feedwater to an adequate pressure for desalination via the RO plant membranes. Due to the extraction of energy from the brine stream, the brine must be pumped away for disposal.

4.3.2.2 Pressure exchanger

The Pressure Exchanger RO plant system modelled is shown below in Figure 32.

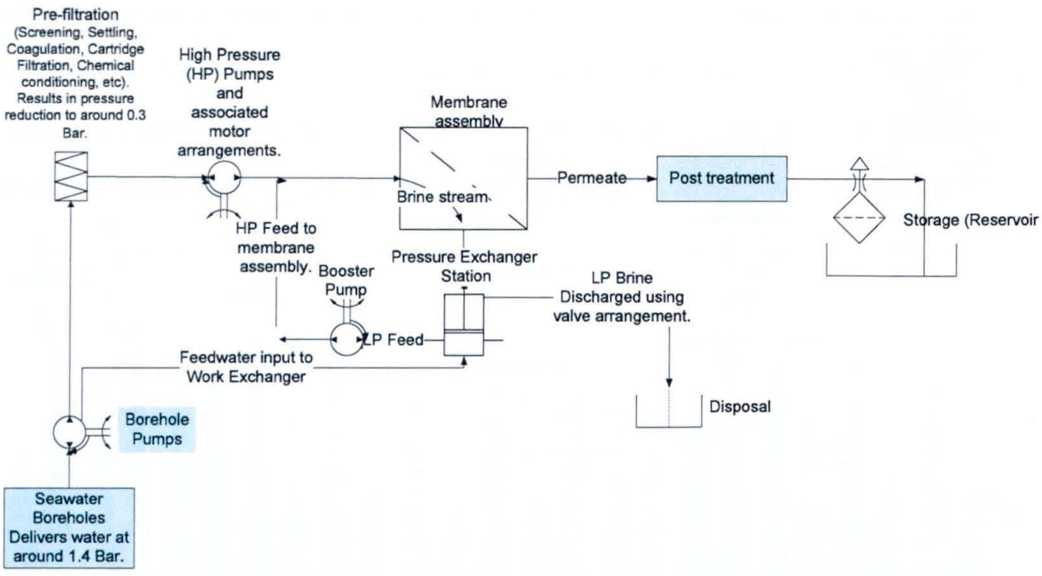

Figure 32: RO plant using Pressure Exchanger for BSR design

As shown in Figure 32 above, the Pressure Exchanger BSR RO plant uses the brine/ concentrate stream to pressurise a hydraulic chamber. This hydraulic chamber acts on a piston arrangement, which in turn is used to partially pressurise the incoming feedwater. A booster pump then raises the now partially-pressurised feedwater to the correct pressure to combine with the feedwater pressurised by the high pressure pump, for desalination by the RO plant membranes.

After pressurising the incoming feedwater, the brine stream (which is still partially pressurised) is discharged using valve arrangements, as a low-pressure brine stream.

The Solar and Tidal Current power plants were sized as the equivalent of the conventional power plant that would need to be installed to achieve and maintain maximum flowrate for the BSR RO plants.

As was the case in Stage 1, additional power was added in discrete levels up to (and including) the power required to achieve five times maximum flowrate of each of the RO plants.

4.3.2.3 Solar power

The power required at each solar power capacity for the BSR RO plants, and the corresponding area of solar panels that are required to achieve it, are tabulated below in Table 15 and Table 16 for the Pelton Wheel and Pressure Exchanger types, respectively.

Table 15: Increments of solar power modelled for Pelton Wheel RO Plant at Massawa

Multiple of maximum flowrate	Non-Intermittent Power Required (MW)	Area of solar panels installed (based on 10% efficiency). (m^2)	Area in square (km^2)	Rated installed capacity, based on 1.44W max/m^2 Units (kW)
1	1	2024150	2.02	2.9
2	2	4048300	4.04	5.8
3	3	6072450	6.07	8.7
4	4	8096600	8.1	11.7
5	5	10120750	10.1	14.6

Table 16: Increments of solar power modelled for Pressure Exchanger RO Plant at Massawa

Multiple of maximum flowrate	Non-Intermittent Power Required (MW)	Area of solar panels installed (based on 10% efficiency). (m^2)	Area in square (km^2)	Rated installed capacity, based on 1.44W max/m^2 Units (kW)
1	0.8	1619320	1.6	2.3
2	1.6	3238640	3.2	4.7
3	2.4	4857960	4.9	7.0
4	3.2	6477280	6.5	9.3
5	4.0	8096600	8.1	11.7

These installed capacities were based on the Sharp 235W Solar Panel which is discussed in section 4.3.1.1.1.

The power settings were modelled and the results are presented at Section 5.2.

4.3.2.4 Tidal current power

The tidal current power plant was increased in size, in stages up to five times the conventional power plant capacity. The tidal current power required for the BSR RO plants, and the corresponding number of SeaGen Units needed to achieve it, are tabulated for the Pelton Wheel and Pressure Exchanger variants in Table 17 and Table 18, respectively.

Table 17: Increments of Tidal Current Power modelled at Newhaven for the Pelton Wheel RO plant

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of SeaGen Units required	Tidal current capacity installed (MW)
1	1.4	4	4.5
2	2.8	8	8.9
3	4.2	12	13.4
4	5.6	16	17.8
5	7.0	20	22.3

Table 18: Increments of Tidal Current Power modelled at Newhaven for the Pressure Exchanger RO Plant

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of SeaGen Units required	Tidal current capacity installed (MW)
1	1.1	3	3.3
2	2.2	6	6.7
3	3.3	9	10.0
4	4.4	12	13.4
5	5.5	15	16.7

The power settings were modelled and the results are presented at section 5.2.

4.3.3 **Stage 3**

There were two aspects to stage 3 as the model attempted to make the scenarios competent. The following were considered:

- Addition of wind power
- Addition of wave power.

The hybridised power (primary power source supplemented with wind or wave energy) is shown below in Figure 33 and Figure 34 for Massawa and Newhaven, respectively.

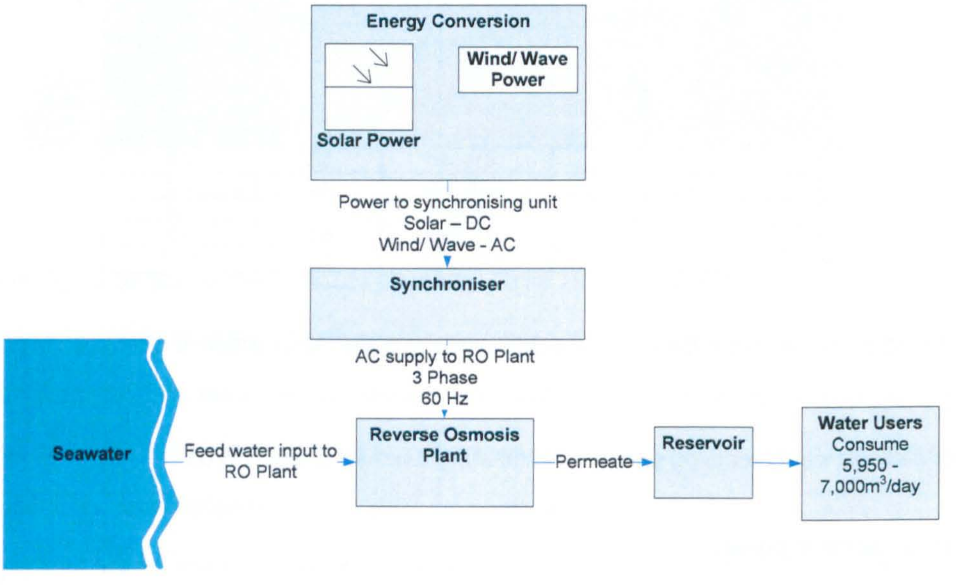

Figure 33: Hybridised Plant at Massawa

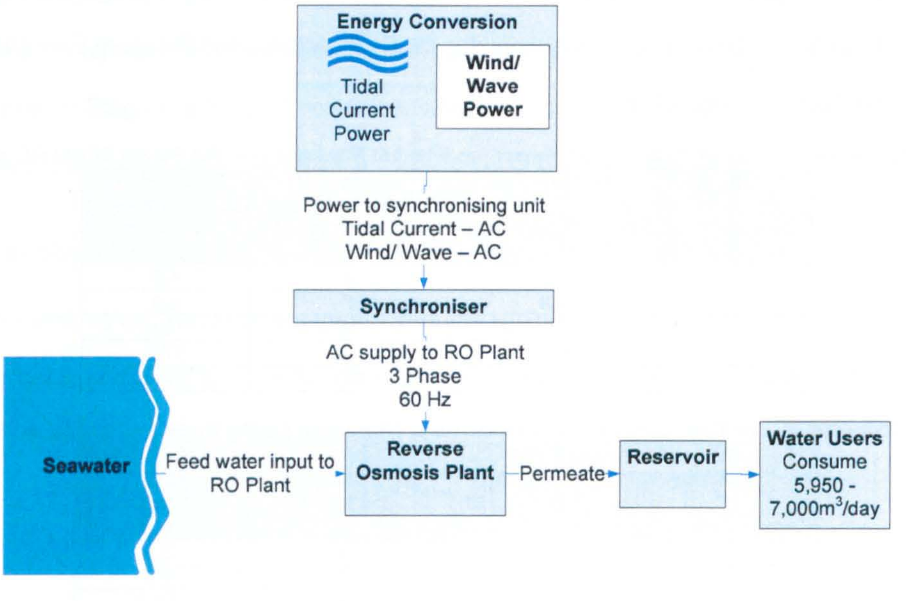

Figure 34: Hybridised Plant at Newhaven

4.3.3.1 Addition of wind power

4.3.3.1.1 Newhaven

The wind resource available at Newhaven was ascertained from the UK wind speed database NOABL[56], and is shown below in Table 19.

Table 19: Average wind speed at Newhaven

Height of reading (m)	Average wind speed (m/s)
10	6
25	6.7

4.3.3.1.2 Massawa

The monthly average data at Massawa was taken from local weather reports[57], and is presented below in Table 20.

Table 20: Average wind speed at Massawa

Data	Wind speed at 10m height (m/s)
Jan	3.576
Feb	3.576
Mar	5.812
Apr	5.812
May	5.812
Jun	5.812
Jul	4.917
Aug	5.364
Sep	4.917
Oct	5.364
Nov	5.364
Dec	5.364
Annual Average	**5.141**

This data was then applied to HOMER to derive the wind speed for each hour of the year which is shown below in Figure 35.

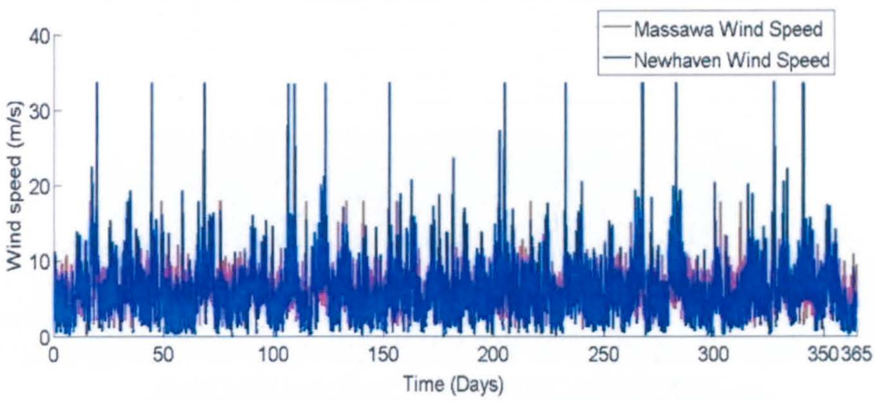

Figure 35: Wind speeds at Massawa and Newhaven over 1 year

---

[56] The data in this database is the result of an air flow model that estimates the effect of topography on wind speed. http://www.rensmart.com/Weather/BERR Newhaven data based on the following coordinates 50.78076029964647 Lat: 0.0473785400390625 long. [Last viewed on 7 August 2011].

[57] Average monthly data taken from http://www.weatherreports.com/Eritrea/Massawa/averages.html and is based on the average of data over 4 years. Coordinates for Massawa 15 36' 35" Lat: 39 27' 00" Long [Last viewed on 7 August 2011].

Wind power was added to the single renewable power source scenarios for No BSR and BSR RO Plants, at varying levels, in an attempt to allow the RO plant to operate at a high level of water production continuously. This hybridised power source was based on the use of 2,000kW turbines based on a scaled-up Fuhrlander 250 operating profile obtained from the HOMER library.

The wind farm installed power was modelled at stages, which increased in size as shown below in Table 21 – Table 26 inclusive.

Table 21: Wind Power at Newhaven - No BSR

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of Wind Turbines required	Wind turbine capacity installed (MW)
1	3.4	2	4.0
2	6.8	4	8.0
3	10.2	6	12.0
4	13.6	8	16.0

Table 22: Wind Power at Massawa - No BSR

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of Wind Turbines required	Wind turbine capacity installed (MW)
1	2.4	2	4.0
2	4.8	3	6.0
3	7.2	4	8.0
4	9.6	6	12.0

Table 23: Wind Power at Newhaven – Pelton Wheel

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of Wind Turbines required	Wind turbine capacity installed (kW)
1	1.4	1	2.0
2	2.8	2	4.0
3	4.2	3	6.0
4	5.6	4	8.0

Table 24: Wind Power at Massawa – Pelton Wheel

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of Wind Turbines required	Wind turbine capacity installed (MW)
1	1.0	1	2.0
2	2.0	2	4.0
3	3.0	3	6.0
4	4.0	4	8.0

Table 25: Wind Power at Newhaven –Pressure Exchanger

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of Wind Turbines required	Wind turbine capacity installed (MW)
1	1.1	1	2.0
2	2.2	2	4.0
3	3.3	3	6.0
4	4.4	4	8.0

Table 26: Wind Power at Massawa – Pressure Exchanger

Multiple of max flowrate	Non-Intermittent Power Required (MW)	Number of Wind Turbines required	Wind turbine capacity installed (MW)
1	0.8	1	2.0
2	1.6	2	4.0
3	2.4	3	6.0
4	3.2	4	8.0

The results at these power settings are presented at section 5.3.1.

4.3.3.2 Addition of wave power

The Wave Dragon was selected to convert wave motion to power, at each site. It is an 'overtopping' wave energy converter and floats slack-moored to allow it to move in the direction of the prevailing waves.

The principle of operation of the Wave Dragon device is illustrated below, based on [GENI, 2009] in Figure 36.

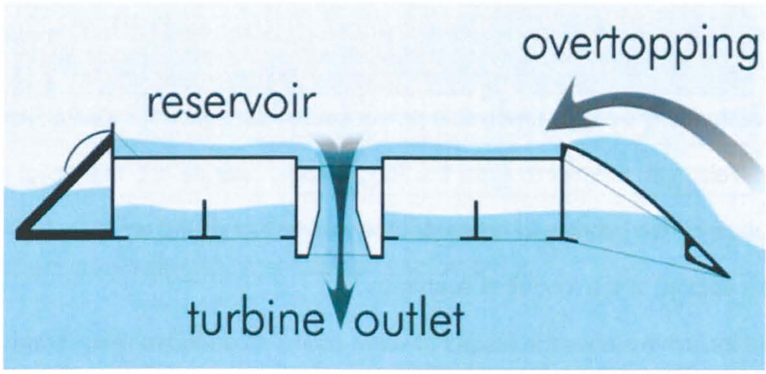

Figure 36: The principle of the Wave Dragon technology

The Wave Dragon works by facing its outstretched collector arms towards the oncoming waves and concentrating the wave front towards the ramp at the front of the structure. As shown in Figure 36 above, energy is captured by waves running up the ramp and overtopping the crest into a reservoir. This water, stored in the reservoir, at a higher level than the sea, is returned through low-head turbines powering electrical generators producing power.

The power production profiles for Massawa and Newhaven are shown below in Figure 37 and Figure 38, respectively, with the maximum values achieved during the year at each site.

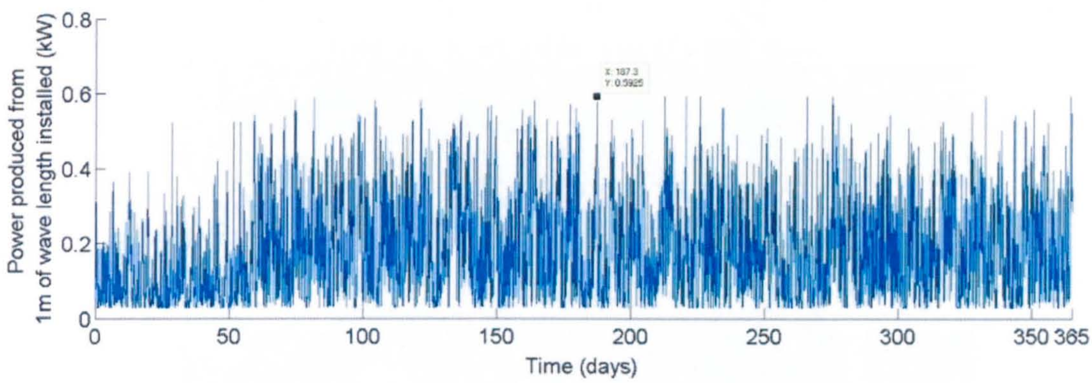

Figure 37: Power produced by 1m of Wave Dragon at Massawa during one year.

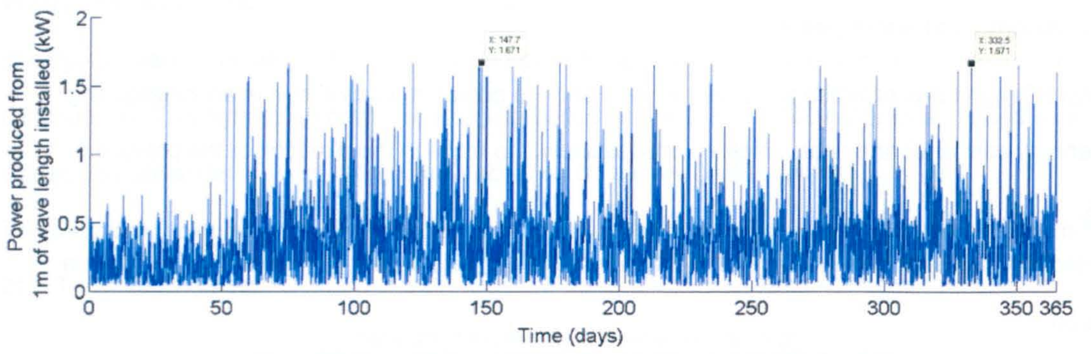

Figure 38: Power produced by 1m of Wave Dragon at Newhaven during one year.

Wave power was added to the single renewable power source scenarios for No BSR and BSR RO Plants, at varying levels in an attempt to allow the RO plants to operate at a high level of water production continuously. This hybridised power source was based on the use of 1.13MW Wave Dragon devices which were applied to the modelled scenarios.

Table 27 –Table 32 inclusive shows the stages of wave power modelled for each scenario.

Table 27: Wave Power at Newhaven - No BSR

Multiple of maximum flowrate	Non-Intermittent Power Required (kW)	Wave Dragon wave front required (km)	No. of 95kW Wave Dragon devices required	Wave Dragon power capacity installed (MW)
1	3.4	2,03	38	3.61
2	6.8	4.07	76	7.22
3	10.2	6.10	114	10.83
4	13.6	8.14	152	14.44

Table 28: Wave Power at Massawa - No BSR

Multiple of maximum flowrate	Non-Intermittent Power Required (kW)	Wave Dragon wave front required (km)	No. of 95kW Wave Dragon devices required	Wave Dragon power capacity installed (MW)
1	2.4	4.05	75	7.13
2	4.8	8.10	150	14.25
3	7.2	12.15	225	21.38
4	9.6	16.20	300	28.50

Table 29: Wave Power at Newhaven – Pelton Wheel

Multiple of maximum flowrate	Non-Intermittent Power Required (kW)	Wave Dragon wave front required (km)	No. of 95kW Wave Dragon devices required	Wave Dragon power capacity installed (MW)
1	1.4	0.8	16	1.52
2	2.8	1.68	32	3.04
3	4.2	2.51	48	4.56
4	5.6	3.35	64	6.08

Table 30: Wave Power at Massawa – Pelton Wheel

Multiple of maximum flowrate	Non-Intermittent Power Required (kW)	Wave Dragon wave front required (km)	No. of 95kW Wave Dragon devices required	Wave Dragon power capacity installed (MW)
1	1.0	1.69	32	3.04
2	2.0	3.38	64	6.08
3	3.0	5.06	96	9.12
4	4.0	6.75	128	12.16

Table 31: Wave Power at Newhaven – Pressure Exchanger

Multiple of maximum flowrate	Non-Intermittent Power Required (kW)	Wave Dragon wave front required (km)	No. of 95kW Wave Dragon devices required	Wave Dragon power capacity installed (MW)
1	1.1	0.66	13	1.24
2	2.2	1.32	26	2.47
3	3.3	1.97	39	3.71
4	4.4	2.63	52	4.94

Table 32: Wave Power at Massawa – Pressure Exchanger

Multiple of maximum flowrate	Non-Intermittent Power Required (kW)	Wave Dragon wave front required (km)	No. of 95kW Wave Dragon devices required	Wave Dragon power capacity installed (MW)
1	0.8	1.35	25	2.38
2	1.6	2.70	50	4.75
3	2.4	4.05	75	7.13
4	3.2	5.40	100	9.50

The results at these power settings are presented at section 5.3.2.

4.3.4 Stage 4

Stage 4 was the use of hydrogen (generated through the utilisation of captured energy), with primary energy and hybridised (primary with wind or wave) power scenarios, for No BSR and BSR RO Plants. This allowed the power captured during normal RO plant operation, to be reapplied at times when insufficient power was being produced to maintain maximum RO plant water production.

The method used to reapply captured power was the hydrogen Polymer Electrolyte Membrane (PEM) Fuel cell. The operation of the PEM Fuel cell is shown below in Figure 39.

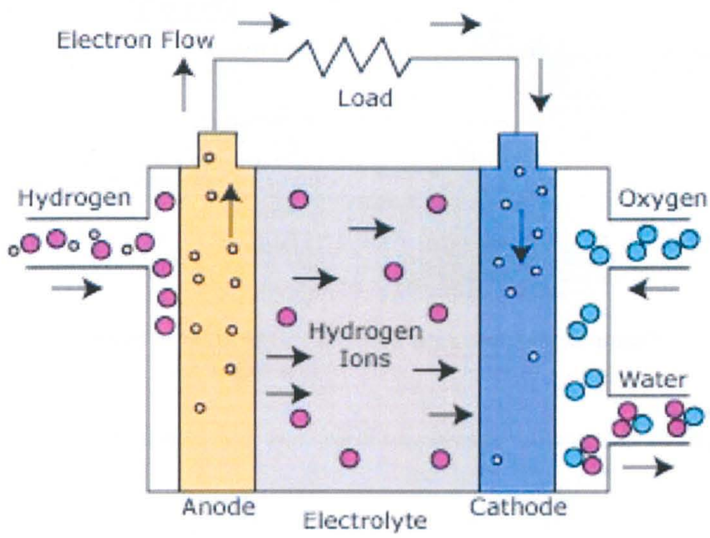

Figure 39: PEM Fuel Cell Operation

The PEM fuel cell uses a solid polymer membrane as the electrolyte. This polymer is permeable to protons when it is saturated with water, but it does not conduct electrons.

The fuel for the PEM fuel cell is hydrogen, and the charge carrier is the hydrogen ion (proton). At the anode, the hydrogen molecule is split into hydrogen ions (protons) and electrons. The hydrogen ions permeate across the electrolyte to the cathode while the electrons flow through an external circuit and produce electric power. Oxygen, in the form of air, is supplied to the cathode, and combines with the electrons and the hydrogen ions to produce water. The reactions at the electrodes are shown below in Table 33.

Table 33: PEM Fuel Cell electrode reactions

Reactions	Chemical formulae
Anode Reactions	$2H_2 => 4H^+ + 4_{e-}$
Cathode Reactions	$O_2 + 4H^+ + 4_{e-} => 2\,H_2O$
Overall Cell Reactions	$2H_2 + O_2 => 2\,H_2O$

PEM fuel cells work as separate cells, and are combined, into stacks to deliver the required power levels. The scenarios that employed the reapplication hydrogen fuel are illustrated below, for Primary Power Scenarios (Figure 40 for Massawa, and Figure 41 for Newhaven) and Hybridised Power Scenarios (Figure 42 for Massawa, and Figure 43 for Newhaven).

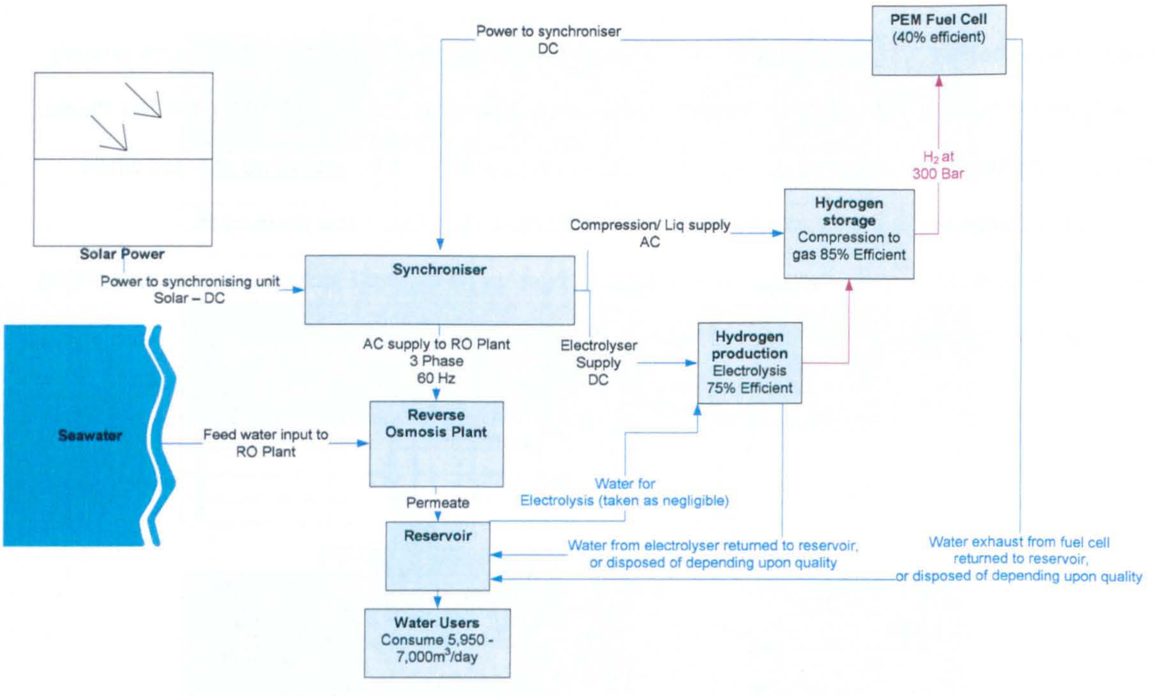

Figure 40: Massawa solar scenario for utilisation of hydrogen.

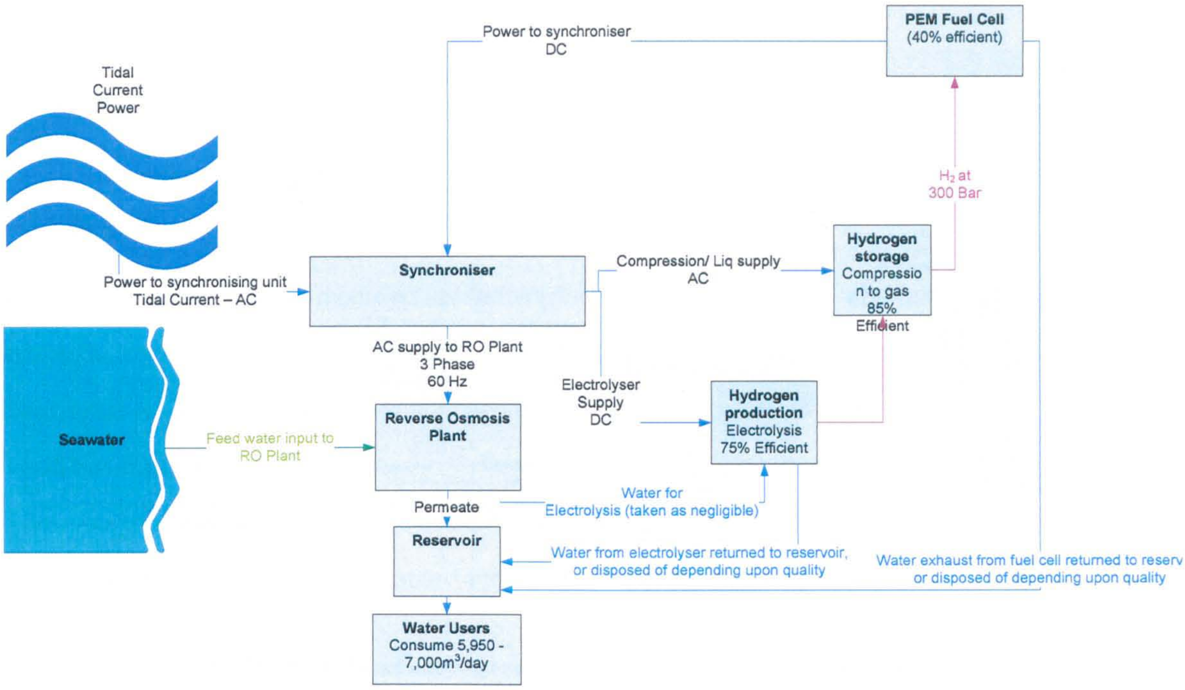

Figure 41: Newhaven Tidal Current scenario for utilisation of hydrogen.

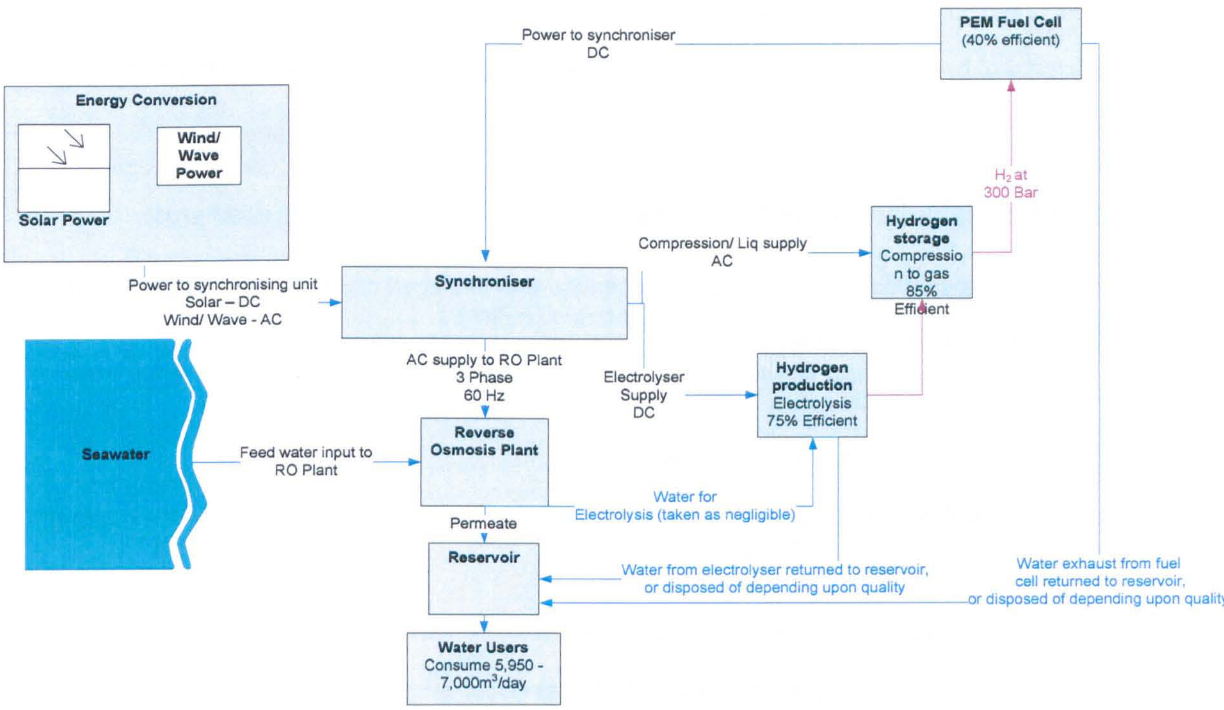

Figure 42: Massawa solar with wind/ wave scenarios for utilisation of hydrogen.

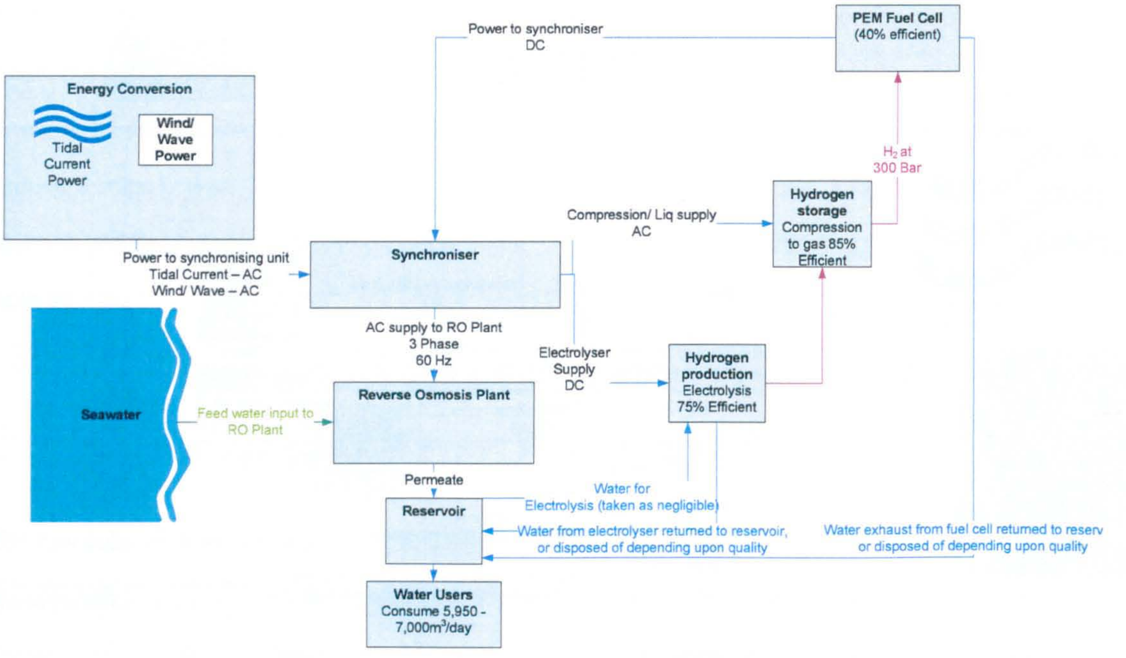

Figure 43: Newhaven Tidal Current with wind/ wave scenarios for utilisation of hydrogen.

The water used and lost due to the electrolysis process as part of the hydrogen fuel cycle is discussed at Appendix C and considered to be negligible.

The efficiency of hydrogen use was taken as 22%. The results are shown at section 5.4, and a discussion of the effectiveness of hydrogen is presented at section 6.2.1.3.

4.4 Scenario calculations and technical competence of modelled scenarios

There were 270 scenarios modelled, and each scenario was managed on its own spreadsheet, which contained the following details for each hour of the year:

- The input renewable power
- The corresponding feedwater temperature
- The power that could be used by the RO plant i.e. power above minimum and below maximum flowrate thresholds
- The power wasted, i.e. power produced minus power outside RO plant operating thresholds
- The water produced during that hour, which was calculated in Matlab using the RO plant operating profiles as discussed at Appendix B.
- The water deficiency/ remaining considering the demands of the local users.

The measure of technical competence of the scenarios was the percentage of the water demand over the course of the year, which the RO plant managed to satisfy.

5 Results

5.1 Stage 1

The results of stage 1 of the modelled scenarios (where varying amounts of renewable power were applied to the No BSR RO plant) are shown below in Figure 44 and Figure 45 for Massawa and Newhaven, respectively. The data is represented in terms of the multiples of non-varying power that would be required to achieve the maximum flowrate from the No BSR RO plant when the greatest renewable power is available. The equivalent solar/ tidal power installed to achieve the maximum flowrate is shown at Table 13 and Table 14 for Massawa and Newhaven, respectively.

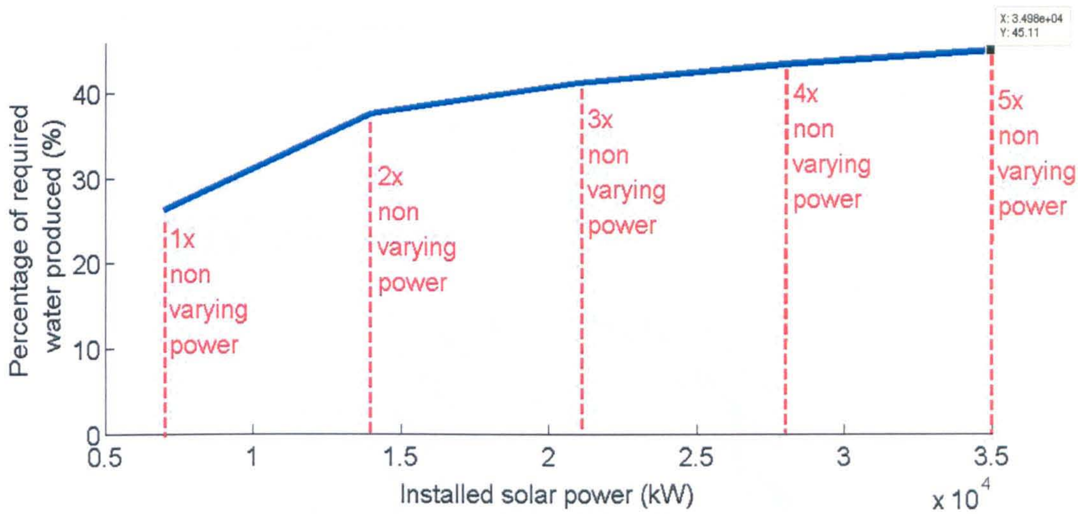

Figure 44: Percentage of water produced at Massawa using solar power

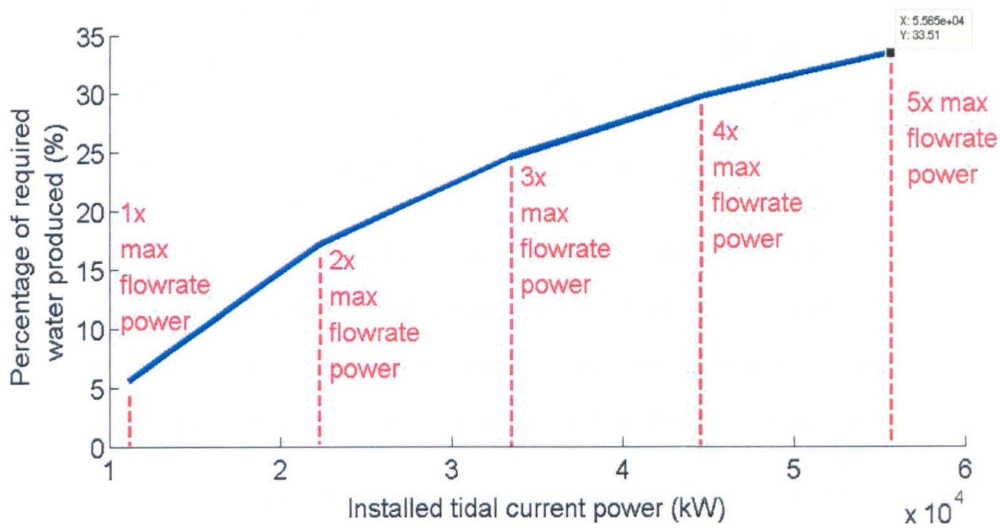

Figure 45: Percentage of water produced at Newhaven using tidal current power

It is evident that the stage 1 modelled scenarios are not able to meet the demands of the local users as at best they only achieve 45% of the users demands.

5.1.1 **Explanation of solar power at Massawa**

Figure 46 below shows the variation of solar power output across a typical solar day, and the effect of increasing the size of the PV array. The curve shown in black is based on the minimum solar power installation that is able, at peak solar irradiation to achieve maximum permeate flow. The dashed red curve shows the limited gain in water output that results from doubling the size of the PV array.

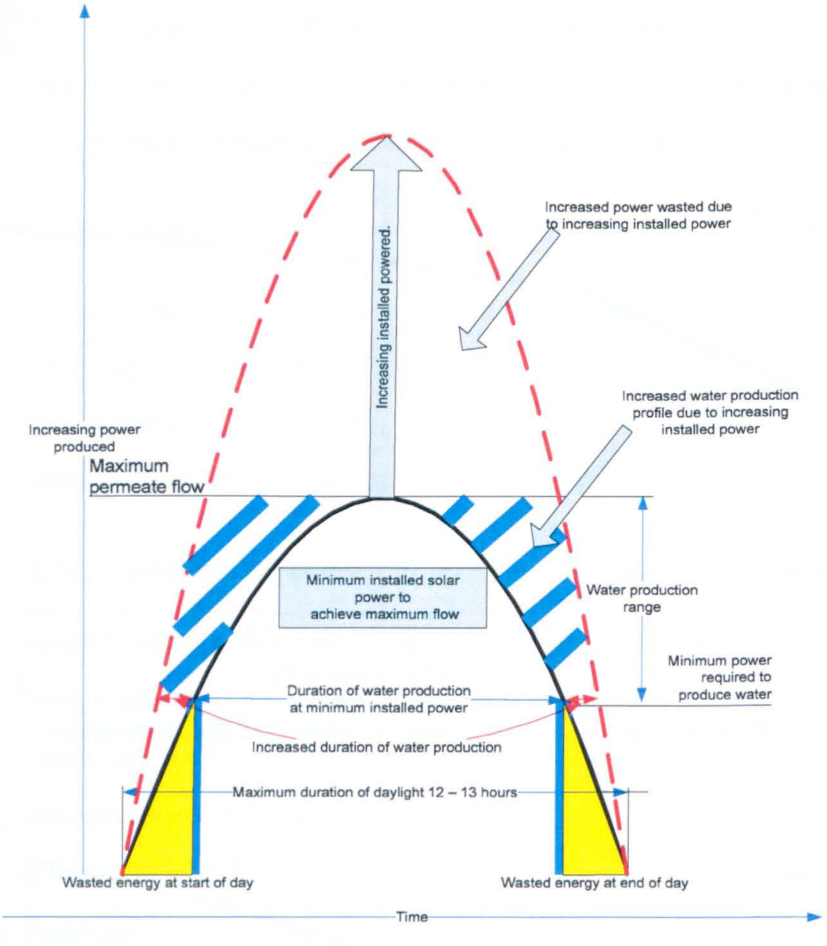

Figure 46: Varying installed solar power.

The sun shines at Massawa for around 12 – 13 hours per day. So, as the RO plant is able to operate for around 50% of the 24-hour day, it is reasonable to expect a maximum of 50% of the required water to be produced from this power source, as increases in installed power would only tend to extend RO plant running time up to the maximum duration of the available sunlight. This is shown by the trend in Figure 44.

It can also be seen that increases in installed solar power tend to also result in a significant amount of wasted power above that required for the maximum permeate production. The wasted power could of course be used for other purposes.

5.1.2 **Explanation of tidal current power at Newhaven**

In light of the inefficiency at low tidal speeds the SeaGen has been modelled as an academic exercise and it was expected that it would not perform particularly well in Newhaven with its slow tidal speeds. This is confirmed by the fact that, when around 1x the generating capacity that would be required by a conventional power source to meet the user needs (3,400kW) is installed as tidal current power by SeaGen devices, they only produce around 6% of the water required.

As the installed tidal current power increases to, in excess of, 5x the non-varying power required to deliver maximum water production (around 17,000kW), the SeaGen devices only manage to achieve around 35% of the water required.

With its double peak in a 24-hour period it seems logical that the tidal cycle should be capable of producing appreciable power (and therefore water) for around 80% of the time with 20 hours per 24-hour day of tidal current movement as shown in Figure 47 below.

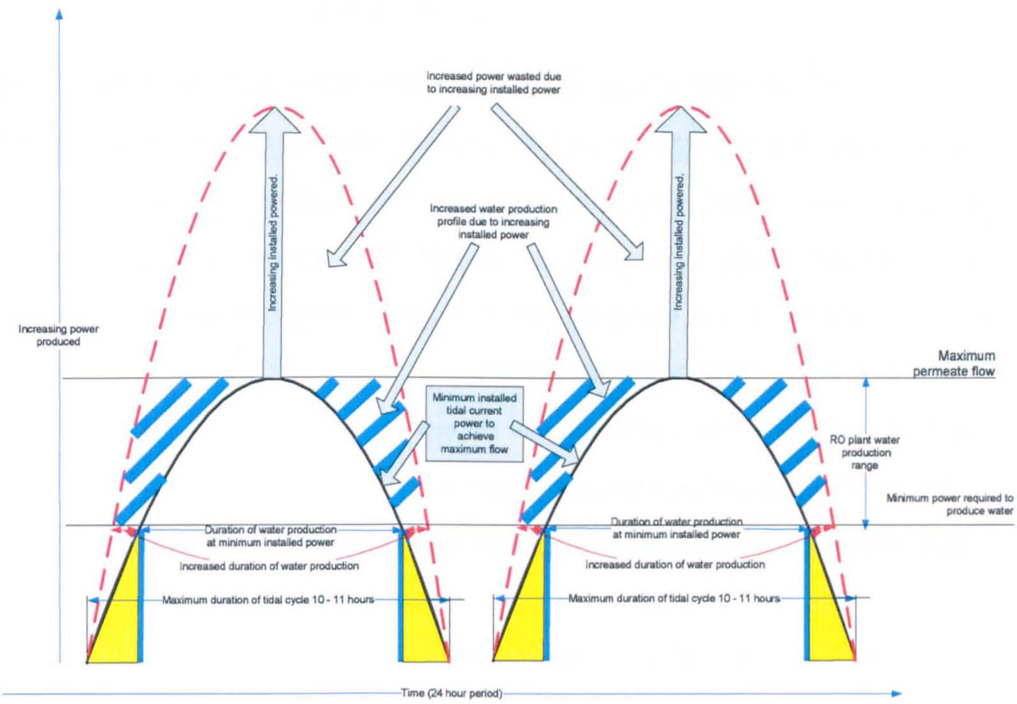

Figure 47: Varying installed tidal current power.

Shown below in Figure 48 is the power output for a single 1,113kW SeaGen device over the course of one year.

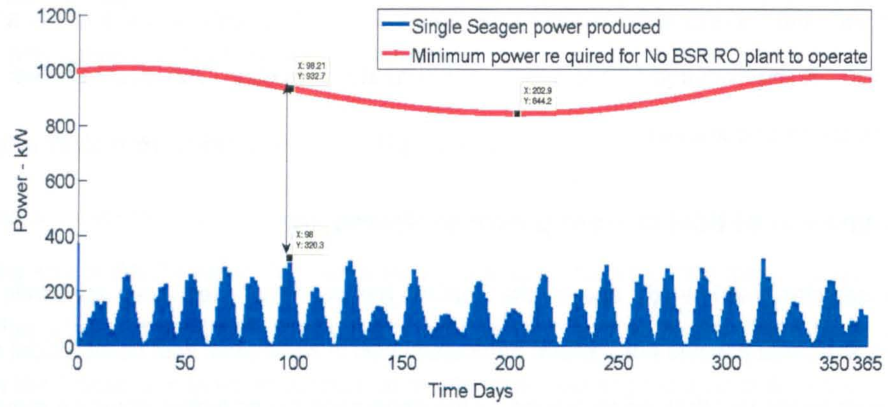

Figure 48: Single SeaGen device power produced at Newhaven compared to the minimum RO plant power requirement.

Although it varies over the course of the year, the minimum power required by the RO plant to operate and produce water is around 845kW, and the maximum modelled power output of 320kW is only slightly over one third of the power required to start to generate water. So although each SeaGen device is rated at 1,113kW, it is evident that the tidal current arrangement modelled does not even start to generate water until multiples of the SeaGen units are installed, and with the extreme undulations of the tidal current profile will, even then, only produce water intermittently.

5.2 Stage 2.

The results for modelled scenarios for Stage 2 (where the Pelton Wheel and Pressure Exchanger BSR RO plants were modelled) at each site achieved the results shown below in Figure 49 and Figure 50 for Massawa and Newhaven, respectively. Each node represents the multiples of conventional power (as per Figure 44 and Figure 45 above) that would be required to achieve maximum flowrate from the particular RO plant in question. The equivalent solar/ tidal power installed is shown above at:

- Table 15 for Massawa Pelton Wheel RO plant
- Table 16 for Massawa Pressure Exchanger RO plant
- Table 17 for Newhaven Pelton Wheel RO plant, and
- Table 18 for Newhaven Pressure Exchanger RO plant.

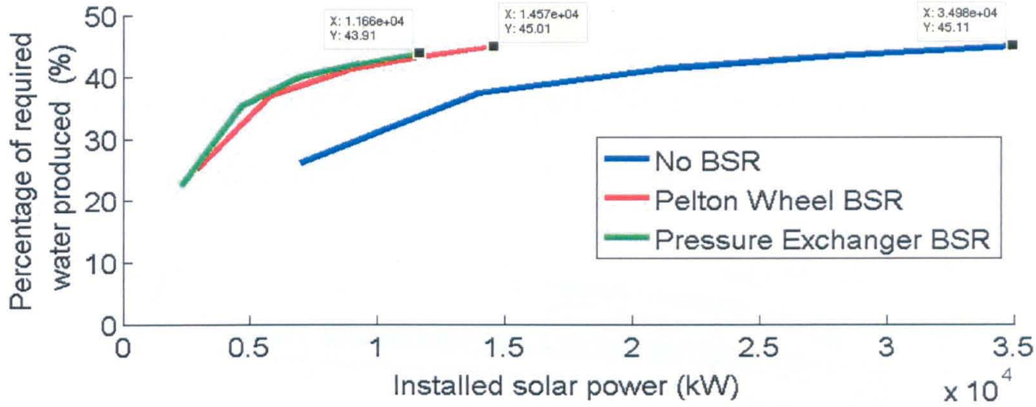

Figure 49: Percentage of water produced at Massawa, using solar power for BSR and No BSR RO plants

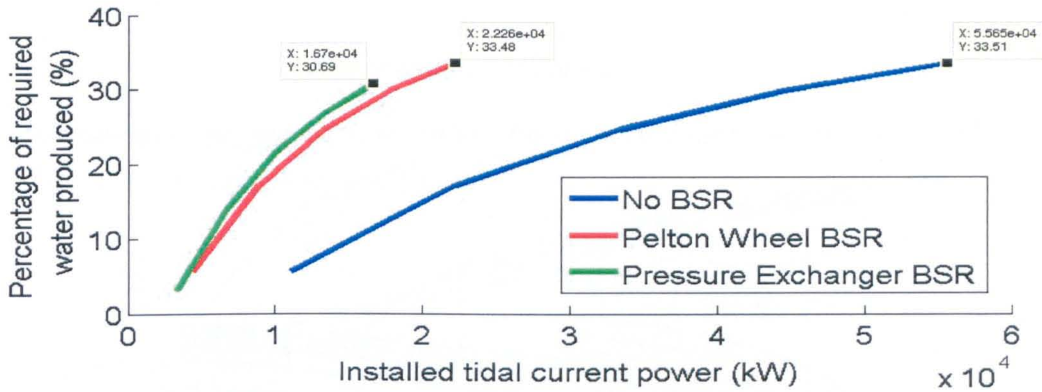

Figure 50: Percentage of water produced at Newhaven, using tidal current power for BSR and No BSR RO plants

As can be seen from the Figures above, within the range modelled, the RO plants with Brine Stream Recovery (BSR) generated approximately the same amount of water as the No BSR RO plant, but employed considerably less energy to do so. This said, the amount of water produced by the BSR variants (being similar to the No BSR RO plant) was not adequate to meet the demands of the local users.

5.3 Stage 3

Stage 3 involved the addition of Wind Power and Wave Power. The figures used to represent the scenarios where wind/ wave power was used show:

- Five single lines of constant primary power set at the levels for the Stage 1 and Stage 2 modelling for No BSR and BSR RO plants, respectively, with
- Additional wind/ wave power added at the levels described in section 4.3.3.

5.3.1 **Addition of Wind**

The results for modelled scenarios for Stage 3, when wind power was used in addition to the primary renewable energy source, are shown below in Figure 51 and Figure 52, for Massawa and Newhaven, respectively.

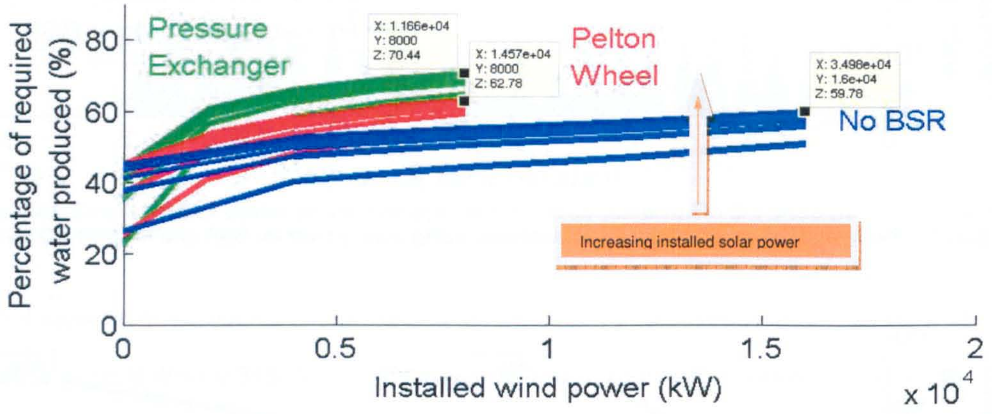

Figure 51: Comparison of the percentage of water produced at Massawa, using solar power supplemented by wind Power

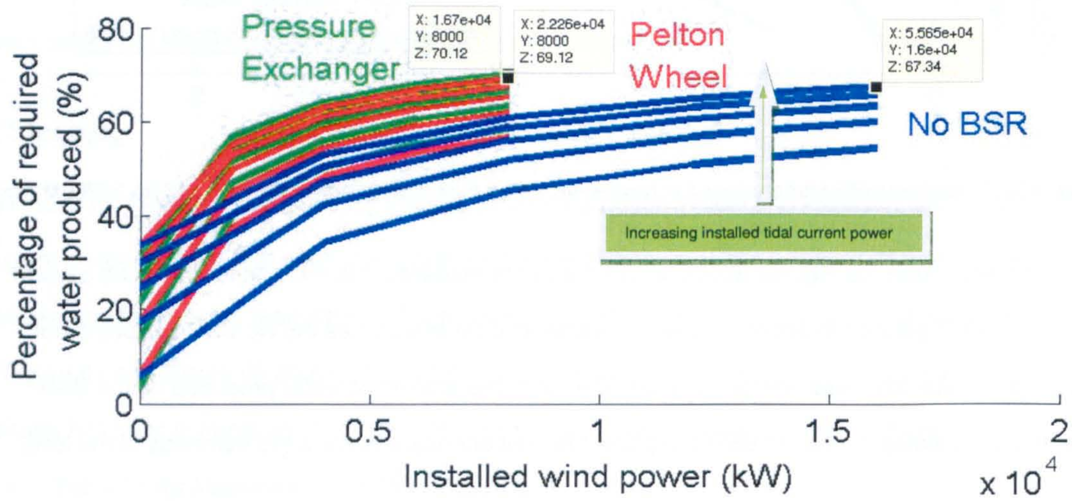

Figure 52: Comparison of the percentage of water produced at Newhaven, using tidal current power supplemented by wind power

The addition of wind power to both sites gives a significant improvement to the water production levels, achieving at best just over 70% of the water required. None of the scenarios modelled, though, was able to produce 100% of the water required.

5.3.2 **Addition of Wave power**

The results for modelled scenarios for Stage 3, when wave power was used in addition to the primary renewable energy source are shown below in Figure 53 and Figure 54, for Massawa and Newhaven, respectively.

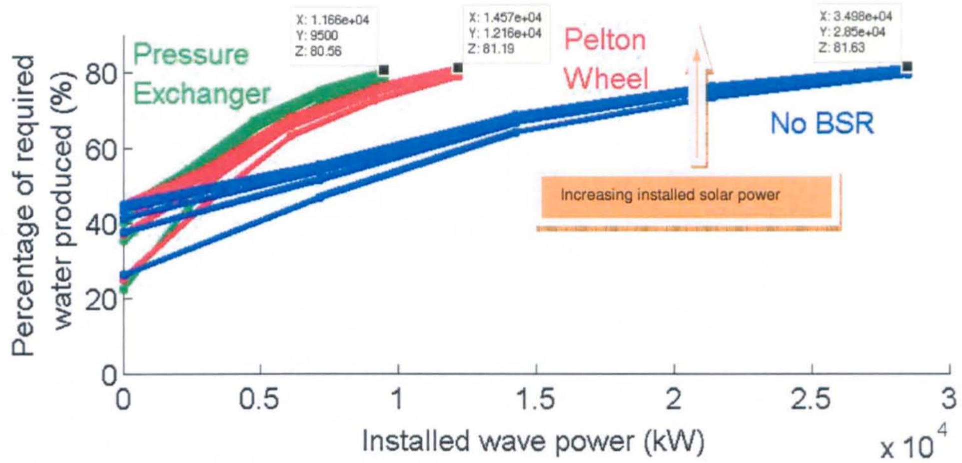

Figure 53: Comparison of the percentage of water produced at Massawa, using solar power supplemented by wave power

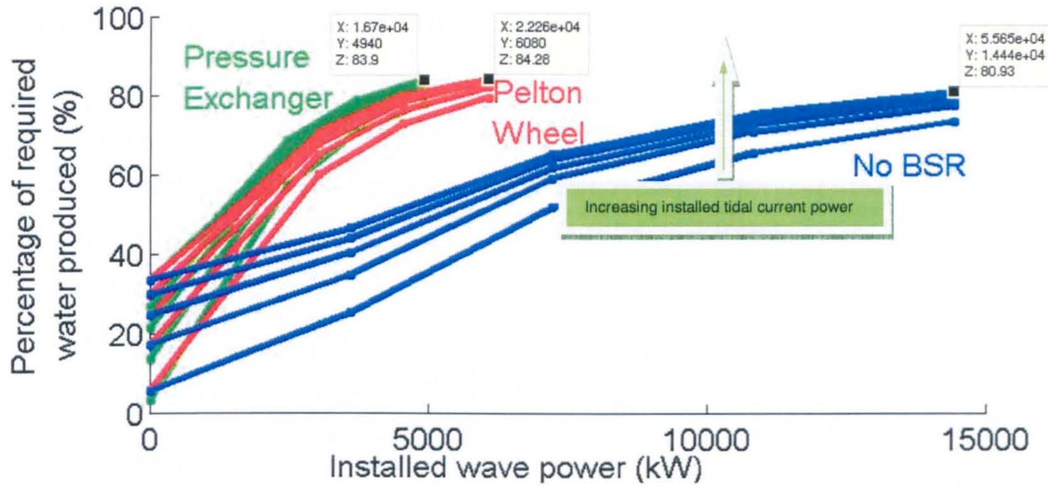

Figure 54: Comparison of the percentage of water produced at Newhaven, using tidal current power supplemented by wave power

As can be seen from Figure 53 and Figure 54 above, the addition of wave power made a substantial improvement to the water production levels at both Massawa and Newhaven, with maximum outputs in excess of 80% of that demanded by the local population. The addition of wave power was more favourable than adding wind power. Once again, none of the scenarios modelled was able to produce 100% of the water required.

5.4 Stage 4

5.4.1 **Stage 1 and 2 scenarios with Hydrogen Fuel**

The results for using Hydrogen after the Stage 1 and 2 scenarios, are shown below in Figure 55 and Figure 56, for Massawa and Newhaven, respectively.

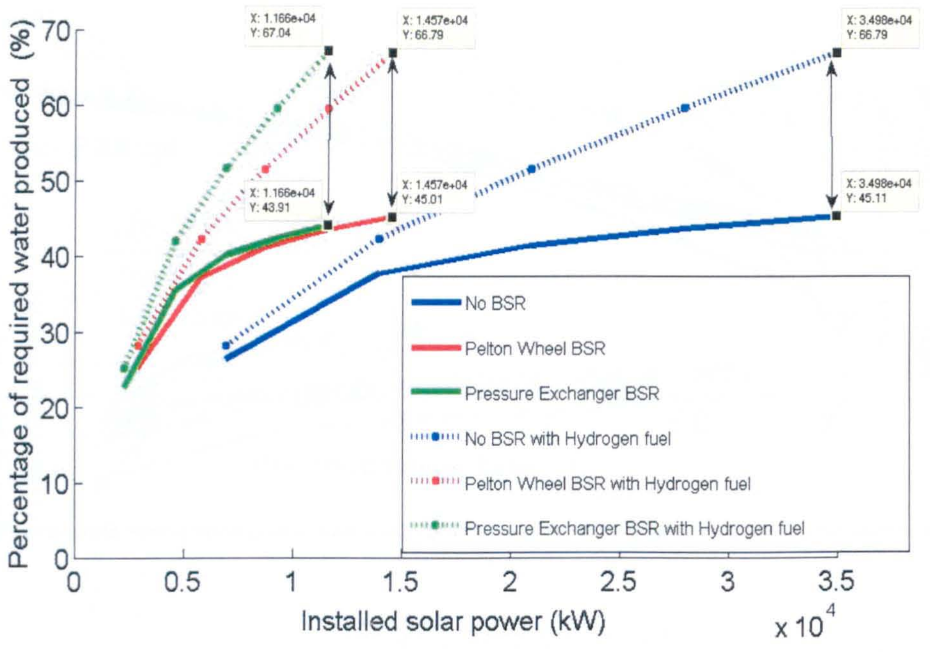

Figure 55: Comparison of the percentage of water produced at Massawa, using solar power with and without hydrogen fuel

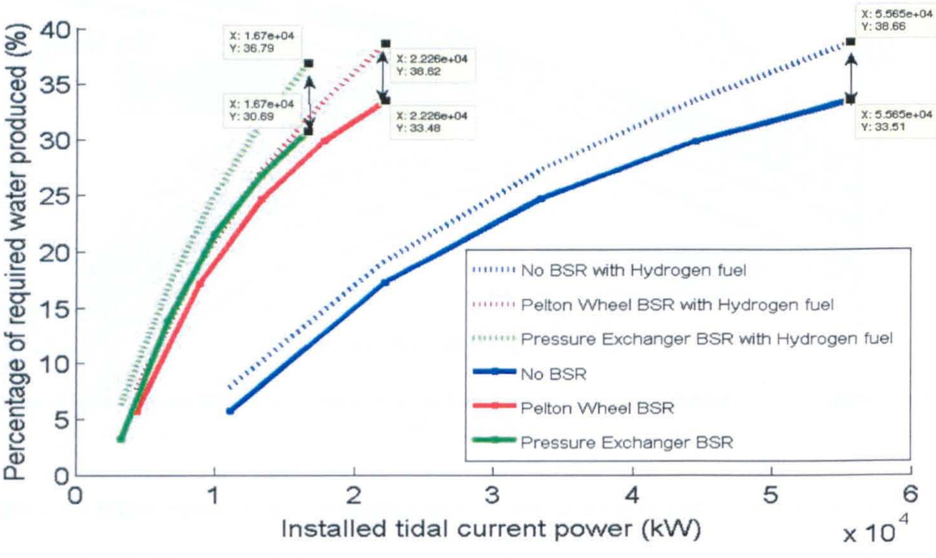

Figure 56: Comparison of the percentage of water produced at Newhaven, using tidal current power with and without hydrogen fuel

As can be seen from Figure 55 and Figure 56 above, the use of hydrogen fuel resulted in a large increase in the amount of water produced, particularly at Massawa, where maximum water production increased by more than 25%.

The increases in water production at Newhaven due to application of hydrogen fuel were more modest, with increases of maximum water production of around 7 to 8%.

As previously, none of the scenarios modelled was able to produce 100% of the water demanded by the local population.

5.4.2 **Massawa**

The results for scenarios for Stage 4, when hydrogen fuel was used at Massawa with Stage 3 (wind or wave power) scenarios, are shown below in Figure 57 and Figure 58, respectively.

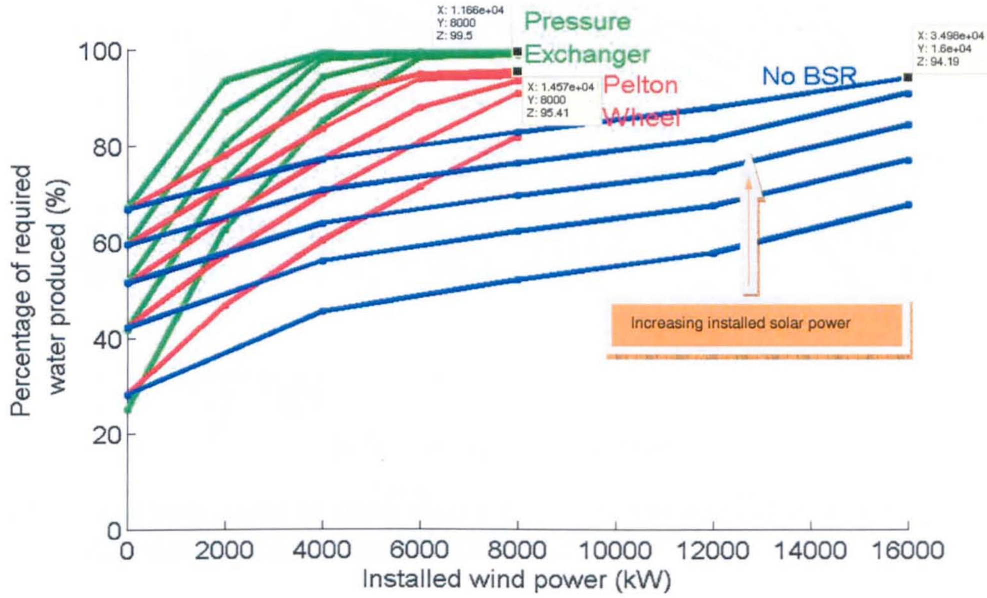

Figure 57: Comparison of the percentage of water produced at Massawa, using solar power supplemented with wind power and hydrogen fuel

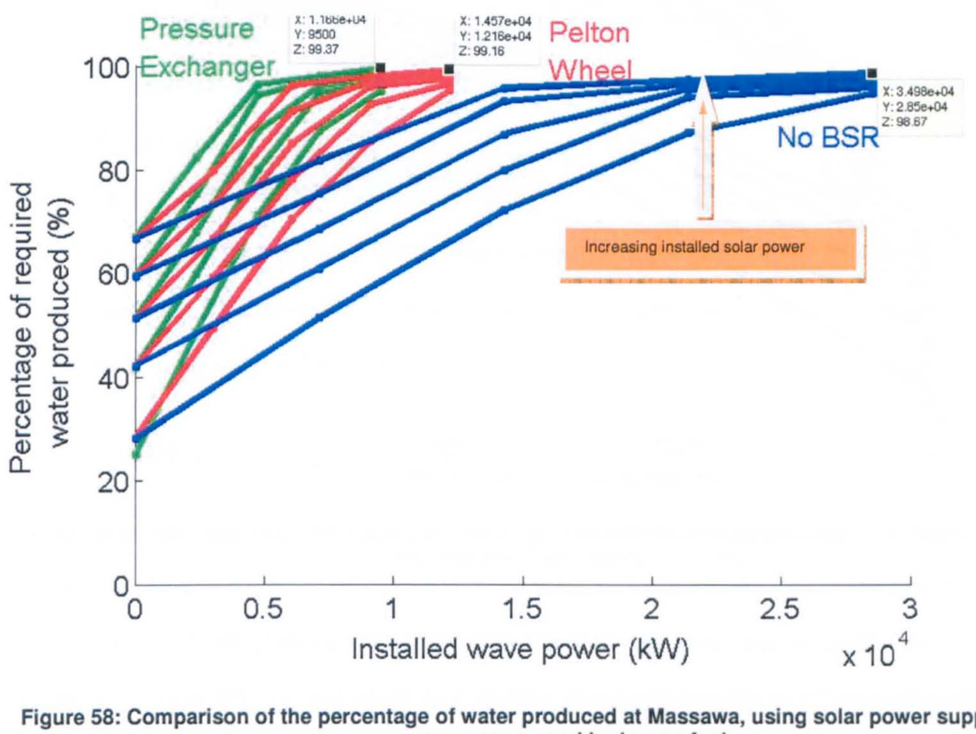

Figure 58: Comparison of the percentage of water produced at Massawa, using solar power supplemented with wave power and hydrogen fuel

5.4.3 **Newhaven**

The results for scenarios for Stage 4, when hydrogen fuel was used at Newhaven with Stage 3 (wind or wave power) scenarios, are shown below at Figure 59 and Figure 60, respectively.

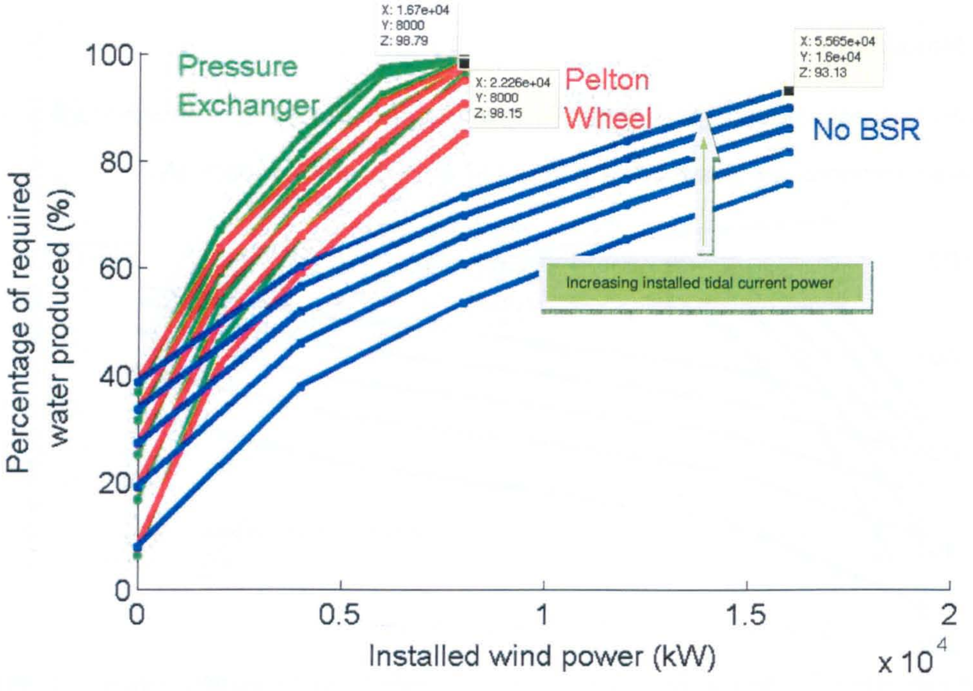

Figure 59: Comparison of the percentage of water produced at Newhaven, using tidal current power supplemented with wind power and hydrogen fuel

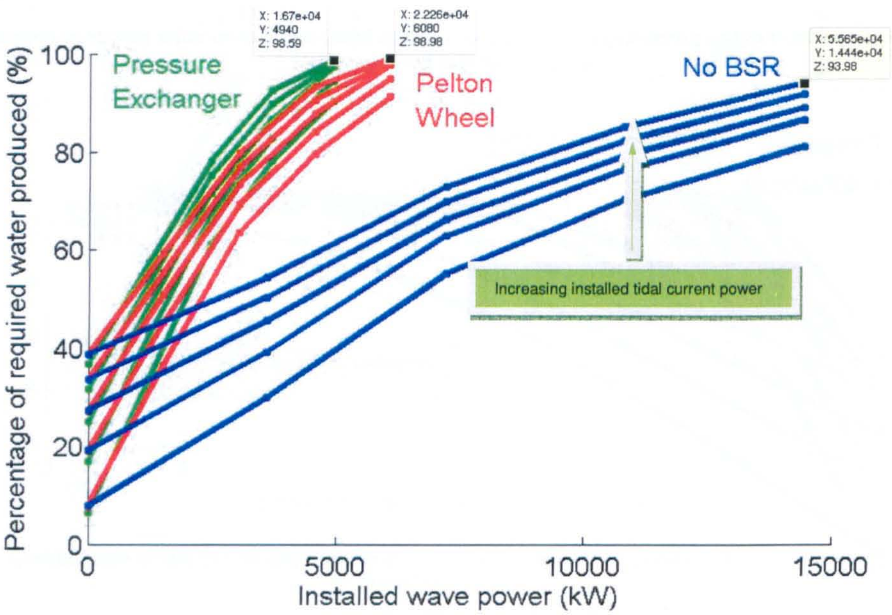

Figure 60: Comparison of the percentage of water produced at Newhaven, using tidal current power supplemented with wave power and hydrogen fuel

As can be seen from the Figures above, the addition of hydrogen fuel at Massawa and Newhaven, enabled the modelled scenarios to achieve maximum outputs, just below 100% of the water required by the local population.

6 Discussion

6.1 Overview

An overview of the discussion section of this research is shown below, in Figure 61.

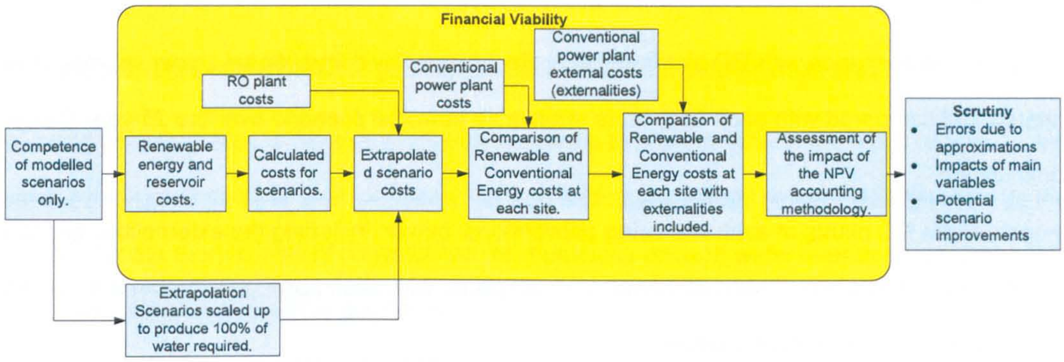

Figure 61: Overview of discussion section

6.1.1 Competence of modelled scenarios

The modelled scenarios were:

- RO plants (BSR and No BSR) designed to produce 7,000m^3/day of water, when operated continuously at the maximum flowrate for 24 hours, and
- RO plants with varying levels and combinations of renewable energy, and identification of how much water these could produce.
- Section 6.2.1 presents the scenarios that were modelled to achieve 90% or more of the water required by the local population over the course of the year.
- Section 6.2.1.3 presents the scenarios with hydrogen fuel and analyses how effective it was at increasing water production.

6.1.2 Financial viability

The financial viability of the modelled scenarios is developed in section 6.3 as follows:

- Cost estimates were made for the renewable energy systems and reservoirs, and
- The RO plant costs were developed for the three variants:
  - No BSR
  - Pelton Wheel BSR, and
  - Pressure Exchanger BSR.
- Each modelled scenario was then made technically competent by scaling-up the installed renewable energy plant, reservoir and RO plant sizes, to produce 100% of the water required.

For example, a scenario that managed to produce 50% of the water required by the local population would have the renewable energy power source(s), reservoir, and RO plant, doubled in size to achieve 100% of the water required.

The scaling factor was then applied to the cost of each scenario, to identify the final cost.

6.1.3 Comparison with conventional scenarios

The costs of the scenarios with RO plants at each site powered by conventional power sources, was estimated and compared with each applicable renewable powered scenario over the 25-year life cycle of the installation.

The costs of the RO plants at each site using conventional power, including the externalities associated with that power source, were then estimated, and compared with each applicable scenario to identify any scenarios that became financially viable.

6.1.4 Application of NPV

The results of this comparison were then assessed using the Net Present Value (NPV) methodology.

6.1.5 Scrutiny

The modelling and results were then further scrutinised to:

- Estimate the impact of approximations on the results, due to the use of polynomials in the modelling exercise
- Account for potential variations in:
    - Diesel fuel cost
    - Solar power production
    - Wind speed
    - Wave height
    - Feed water temperature, and
    - The impact of intermittent operation on the RO plant.
- Identify variations on scenarios that could have an impact on the results.

6.2 Competence of modelled scenarios and effectiveness of energy storage

The objective of the research was to assess the viability of renewable energy sources to meet a fundamental and significant need, un-assisted by conventional power, in this case, to provide 7,000m^3 of water per day by desalinating seawater at Massawa and Newhaven. The RO plants were sized to produce this amount of water, if run continuously at maximum output, 24 hours per day.

The section below presents the conclusions from the modelled scenarios that were able to provide 90% or more of the water required and section 6.2.1.3 provides details of the effectiveness of energy storage and reuse.

6.2.1 Modelled scenarios that produced over 90% of water demand.

The following section presents the scenarios that were able to provide 90% of the water required, using renewable power and hydrogen fuel for energy storage and reuse. Ninety percent was selected as the 'cut-off' point for the assessment of competence, as it provides enough water over the course of a year to sustain the population with minimal discomfort.

There were 85 scenarios out of 270 (31%) that were able to achieve over 90% of the required output.

The results indicate that only the scenarios that employed hydrogen fuel, were able to achieve 90% or more of the water required.

Two criteria are used to ascertain the best technical option at each site:

- Production of over 90% of the water required with the least installed power, and
- Production of the most water.

The resulting water produced vs. installed power vs. percentage of primary power installed relationships, are shown below in Figure 62 and Figure 63 for Massawa and Newhaven, respectively.

These Figures also show the best option at each site based on the least power used and maximum water produced.

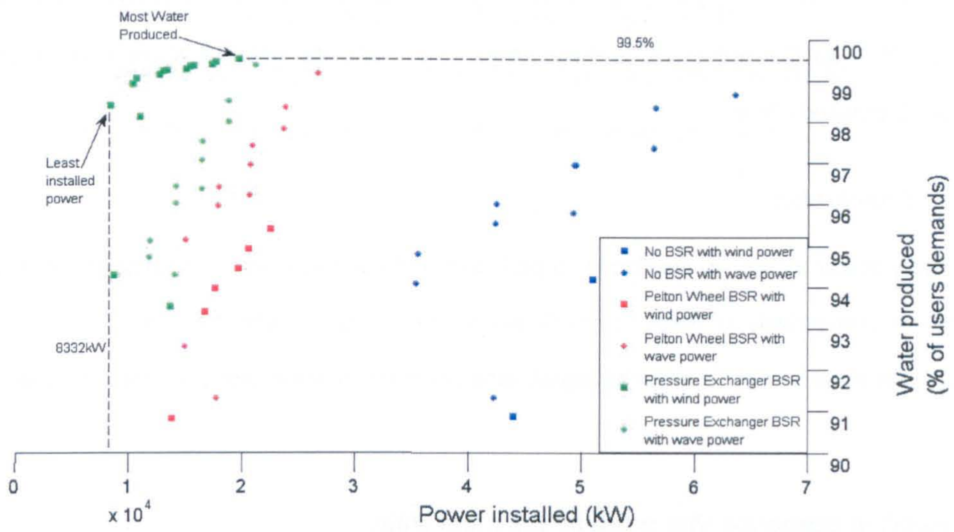

Figure 62: Massawa – Over 90% water produced vs. Power installed

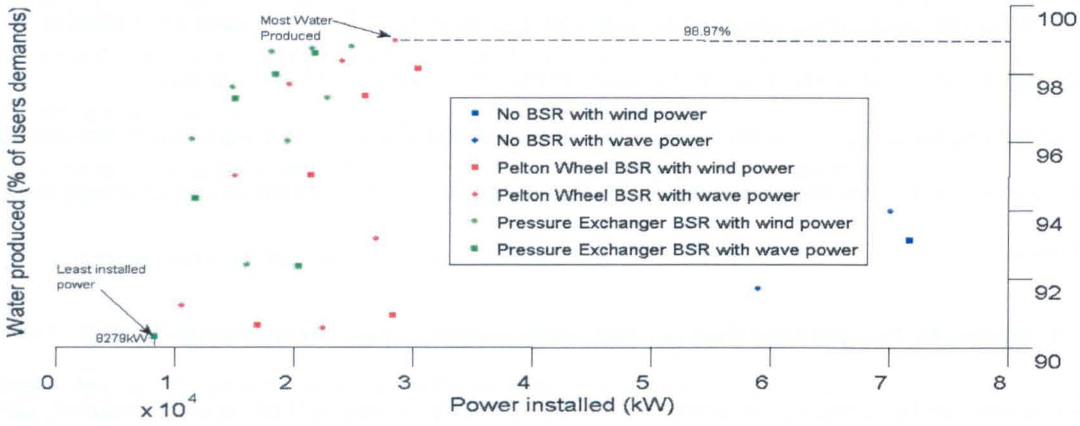

Figure 63: Newhaven – Over 90% water produced vs. Power installed

6.2.1.1 Over 90% produced with the least installed power

The following section identifies the scenarios that produced over 90% of the water required, with the minimum installed power.

6.2.1.1.1 Massawa

The Pressure Exchanger BSR RO plant produced 98.4% of the water required, using the least amount of installed power at Massawa. It employed a combination of 8,331.8kW of installed solar and wind power (made up of 28% Solar and 72% Wind power) with a specific installed power-to-water production ratio of 0.0033 installed kW/m^3.

6.2.1.1.2 Newhaven

The Pressure Exchanger BSR RO plant produced 90.3% of the water required, using the least installed power at Newhaven. It employed a combination of 8,279kW of installed tidal current and wave power, (made up of 40% Tidal Current and 60% Wave power) with a specific installed power-to-water production ratio of 0.0036 installed kW/m^3.

6.2.1.1.3 Conclusion

Supplementary power makes up the dominant part (over 70% and 60% of the input power at Massawa and Newhaven, respectively) of these most efficient scenarios. As expected, due to the higher feedwater temperature, the Massawa plant requires slightly less power/m^3 of water produced than the plant at Newhaven.

6.2.1.2 Modelled scenarios that produce the most water

The following section identifies the scenarios that produce the most water for the local population.

6.2.1.2.1 Massawa

The Pressure Exchanger BSR RO plant produced the most water at Massawa (99.5% of the water required by the local population) using a combination of 19,659.1kW of installed solar and wind power (made up of 59% Solar and 41% Wind power) with a specific installed power-to-water production ratio of 0.0077kW/m^3. This is more than double the 0.0033 installed kW/m^3 of the most efficient option when producing at least 90% of the water demanded.

6.2.1.2.2 Newhaven

The Pelton Wheel BSR RO plant produced the most water at Newhaven (98.79% of the water required by the local population) using a combination of 28340kW of installed tidal current and wave power (made up of 79% Tidal Current and 21% Wave power) with a specific installed power to water production ratio of 0.0112kW/m^3. This is more than three times the 0.0036 installed kW/m^3 of the most efficient option when producing at least 90% of the water demanded.

6.2.1.2.3 Conclusion

The above scenarios, for the maximum water produced, required much more installed power, (some 20 - 25 times the power required to maintain full flow if a non-varying power source was used[58]), and in both cases the primary (solar and tidal current) power was the dominant part of the combination. This is in contrast to the least power installed scenarios, where the secondary power source (wind/ wave energy) was dominant. The water production profiles are (although tending towards increased water production for increasing installed power) quite erratic. This is due to the weighting of primary and secondary power for each scenario, which is shown to great effect at Massawa in Figure 64 below, where the installed power was more than doubled, (mainly due to the addition of primary power, which increased from 28% of the total power to almost 60%) to achieve a 1.1% increase in water production.

[58] Based on the non-intermittent power required for BSR RO plants detailed at Section 4.3.3.

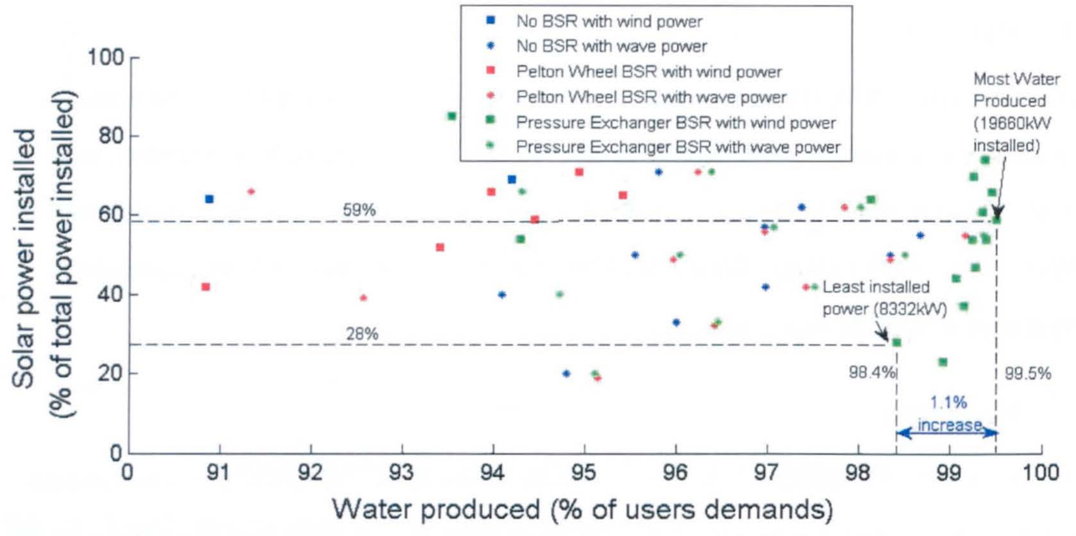

Figure 64: Massawa – Comparison of water produced vs. percentage of solar power installed

It is therefore concluded that the weighting of the primary and secondary energy sources is vitally important if water is to be produced with the best efficiency.

6.2.1.3 Effectiveness of captured energy re-use

The ratio employed to indicate the effectiveness of hydrogen fuel, is a ratio termed the Coefficient of Performance (CoP).

The CoP is derived for each scenario as follows:

$$CoP = Ad_{wat}/En_{was}$$

where:

Ad_{wat} = Percentage of additional water produced by using hydrogen fuel

En_{was} = Percentage of energy that was wasted.

This produced a unit that provides an indication of the effectiveness of using hydrogen fuel.

The larger the CoP for a scenario, the more effective that scenario is in the use of hydrogen fuel to desalinate water.

The CoPs for each scenario that employed hydrogen fuel were collated, and the results are presented below for each site and RO plant type modelled.

6.2.1.3.1 Massawa

No BSR

The best return from stored hydrogen power for the No BSR system was when wind energy was used, at a CoP of just under 0.79. The modelled scenario was made up of 34,975kW of installed solar power and

16,000kW of installed wind power which was the largest scenario modelled. This is compared to the CoP of 0.715, with 34,975kW of installed solar power and 7,125kW of installed wave power.

Pelton Wheel BSR

The best return from stored hydrogen power for the Pelton Wheel BSR system was a CoP of just over 0.8 when 2,915kW of solar power was installed.

Pressure Exchanger BSR

The best return from stored hydrogen power for the Pressure Exchanger BSR system was a CoP of just under 0.794. The modelled scenario was made up of 11,659kW of installed solar power and 2,000kW of installed wind power, which was the largest scenario modelled on the basis of installed power. This is compared to the CoP of just under 0.78 with 11,659kW of installed solar power and 2,375kW of installed wave power.

Overall

The best return from stored power was achieved by the Pelton Wheel BSR system, when solar powered only.

6.2.1.3.2 Newhaven

No BSR

The best return from stored hydrogen power for the No BSR system was a CoP of 0.765, for 11,130kW of tidal current power installed.

Pelton Wheel BSR

The best return from stored hydrogen power for the Pelton Wheel BSR system was a CoP of 0.725, for 4,452kW of tidal current power installed.

Pressure Exchanger BSR

The best return from stored hydrogen power was a CoP of just under 1.4, for 3,339kW of tidal current power installed.

Overall

The best return from stored power was achieved by the Pressure Exchanger BSR RO system, which was powered by tidal current only.

In this case, 72% of the power produced by the tidal current devices was wasted as it was generally below the level required for the RO plant to operate, and only produced just over 3% of the water required by the local users. This was the lowest of the outputs from the scenarios. The use of hydrogen fuel raised the amount of water produced to around 6.3% of the water required. Although more than double the original volume of water, this was the lowest output any of the modelled scenarios using hydrogen fuel.

6.3 Financial Viability

The cost associated with the use of renewable energy and energy storage is a large factor in their viability. So, the next stage was to assess the financial viability of the modelled scenarios

6.3.1 Exchange rates

The estimated costs for the financial modelling exercise were taken from a variety of international sources, and the exchange rates employed to align with pounds sterling (£) are shown below in Table 34 taken from www.x-rates.com on Tuesday 14 December 2010.

Table 34: Exchange rates used for financial modelling

	$US	$GBP	$Cdn	€EUR
$US	1	1.57238	0.993117	1.3669
£GBP	0.635976	1	0.631599	0.843749
$Cdn	1.00693	1.58328	1	1.33589
€EUR	0.75375	1.18518	0.748562	1

6.3.2 Renewable energy costs

The following section provides indicative costs for the renewable energy assets.

6.3.2.1 Solar power

There is some variance within the cost estimates of Photovoltaic (PV) cells.

There is an estimation of 5500 €/kW in 'Totally Renewable Energy Supply' [Keramane, 2008a] (£4,641/kW) for general PV and the Grantham Institute for Climate Change [Ekins-Daukes, 2009] estimates 1,400$/kW (£890/kW).

A Price Waterhouse study [PwC, 2010] concludes that the costs will be in the range 2500 – 5100 €/kW (2,109 – 4,303£/kW) with operation and maintenance (O & M) costs of 15 – 26€/kW/annum (12.66 – 21.94£/kW/annum).

On the basis of the estimates above, the costs for solar power at Massawa were modelled as follows:

- Installation costs - £3,000/kW
- O&M costs - £15/kW/annum.

6.3.2.2 Tidal Current

The 'System Level Design, Performance, Cost and Economic Assessment – San Francisco Tidal In-Stream Power Plant' [Previsic, 2006] estimated the following costs:

- Installation costs[59] – 2,026$/ kW (£1,288/kW)
- O&M costs[60] – 80$/kW/annum (£51/kW/annum).

These estimates were employed for the modelling.

6.3.2.3 Wind

The wind power employed for this exercise was onshore wind power.

Three examples of wind costs were considered:

- The UK Department of Trade and Industry [DTI], which gave a cost of £819/kW (and was very close to the estimate of £844/kW in 'Totally Renewable Energy Supply' [Keramane, 2008b] installed with £44.4/kW for O&M[61]
- The Royal Academy [PB, 2004a] which gave capital costs of £740/kW, and annual operation and maintenance costs of £24/kW[62].
- The update of powering the nation – 'Powering the Future' [PB, 2009] gave capital costs of £1200/kW, and annual operation and maintenance costs of £37.6kW/annum.

Of the above options, 'The update of powering the nation – Powering the Future' gave the most recent figures and so, the costs for Wind Power at Newhaven and Massawa were modelled as follows.

- Installation costs - £1,200/kW
- O&M costs - £37/kW/annum.

[59] Based on a 40 SeaGen turbine site.

[60] It is noteworthy that this figure includes $30 (£19) for insurance.

[61] This was based on an 80MW Park, and quotes 2006 prices.

[62] These costs were based on a windpark of 24MW.

6.3.2.4 Wave

The costs associated with the Wave Dragon are not well established as it is still at the prototype stage, but indicative figures were £4,000/kW [Wilson, 2011] or 4,000€/kW [Soerenson, 2006] for installation and O&M costs of £57/kW/annum, based on offshore wind estimates [PB, 2004b], or £27/kW/annum [Wilson, 2011].

The purposes of this research, the latest estimates were adopted which were:

- Installation costs - £4,000/kW
- O&M costs - £27/kW/annum.

6.3.2.5 Synchronisation systems

It is assumed that:

- All synchronisation activities can be conducted with simple:
  - Rectifiers for AC – DC conversions
  - Inverters for DC – AC conversions.
- Wind power conversion for use by the RO plant is conducted using transformers.
- The power from all combined renewable energy (hybrid) scenarios are converted within the synchronisation unit(s) to an acceptable DC form before conversion to AC and application to the RO plant pumping system.
- The costs for synchronisation (power conversion) are included within the installation and O&M costs for the individual renewable power source costs.

6.3.2.6 Captured energy storage and reuse

6.3.2.6.1 Conversion to hydrogen

'The Feasibility, Costs and Markets for Hydrogen Production' [AEA, 2002] quotes costs of £170/kW when hydrogen is generated by electrolysis at MW scales, as would be the case in the RO plant scenarios proposed.

This figure (although not stated) appears to refer to alkaline electrolysers, and includes the costs associated with the power to operate the electrolyser.

In the case of the scenarios being modelled, the captured power to operate the electrolyser is taken as a free resource, as it would have otherwise been wasted. So only the capital cost of the electrolyser, and its O&M costs were modelled.

'Hydrogen-based autonomous power systems: techno-economic analysis of the integration of Hydrogen in Autonomous Power Systems' [Zoulias, 2008] quotes full PEM electrolyser system costs[63] of:

- 1565 €/kW_{el}, and
- 3130 €/kW_{H2}.

A standing cost of 2% of the electrolyser cost per year is taken to cover all aspects of O&M.

Hydrogen Conversion Costs

On the basis of the information above, the costs for electrolysis at Newhaven and Massawa were modelled as follows:

- Installation costs - £1,320/kW[64]
- O&M costs - £26/kW/annum.

6.3.2.6.2 Hydrogen storage

The costs quoted in 'The Handbook of Hydrogen Storage' [Hirsher, 2010], range from 40€/kWh for tanks capable of storing hydrogen up to 350bar, to 150€/kWh for tanks capable of storing up to 700bar. Lower cost tanks were used in the modelling for this research, as the pressure of the gas is not expected to exceed 300bar, and a standing cost of 2% of the cost of the tank per year was applied to include all aspects of O&M.

Hydrogen Storage Cost

The modelling of the hydrogen storage in this research is based on each component in the hydrogen fuel system operating at the efficiencies shown in Figure 65 below, which shows how one kWh of power captured reduces as it goes through the hydrogen conversion and reuse process.

[63] Taken to include all required hydrogen compression requirements up to 300bar.

[64] The electrolyser for a given scenario will be sized and costed based on the greatest conversion required during one hour to generate hydrogen using captured energy.

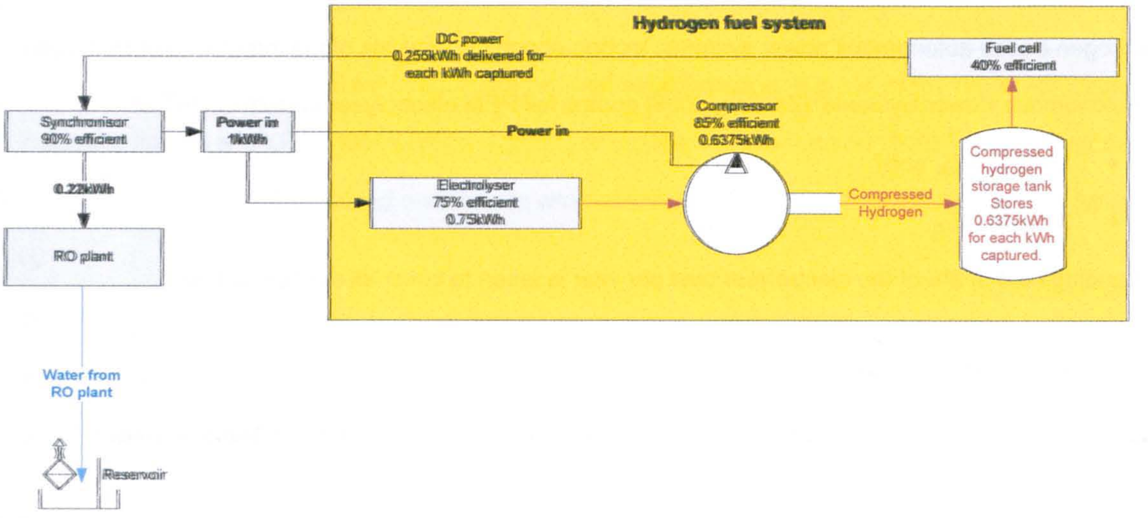

Figure 65: Efficiency of hydrogen fuel system components

It can be seen that the hydrogen stored represents 63.75% of the power captured.

On the basis of the information above, the costs for compressed hydrogen storage at Newhaven and Massawa were modelled as follows:

- Installation costs - £30.15/kWh storage capacity
- O&M costs - £2.43/kWh storage capacity/annum[65].

This is still relatively high when compared to the 'high' case of a 350bar system of \$17.1 (£10.88)/kWh presented in 'Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications' [Lasher, 2009] but was adopted as it is assumed that a hydrogen storage facility of the size envisaged would be a bespoke installation.

6.3.2.6.3 Reuse of captured energy - Fuel Cells

It is stated in 'Hydrogen and Fuel cells' [Hordeski, 2009] that:

> *'... fuel cells can cost \$4000/kW' and that the 'investment cost today (based on 2008) is approximately 5,500\$/kW... .'.*

The maintenance costs for PEM fuel cells have been estimated by [Shipley and Elliot, 2004] as \$71/kW.

On the basis of the information above, the costs for the PEM fuel cell at Newhaven and Massawa were modelled as follows:

- Installation costs - £3,500/kW[66]

---

[65] The hydrogen storage required for a given scenario will be sized and costed based on 63.75% of the greatest power captured within one hour during the year. This equates to an installation cost of £19.22/kWh of captured power and 0.384/kWh storage capacity/annum.

[66] The PEM fuel cells required for a given scenario will be sized and costed based on the greatest hydrogen to electrical power conversion required during 1 hour.

- O&M costs - £45/kW/annum.

6.3.2.7 Cost of Reservoirs

The cost of reservoirs is shown below in Figure 66 and is based on a presentation to the 2008 British Columbia Water and Waste Association Conference [Boyle, 2008].

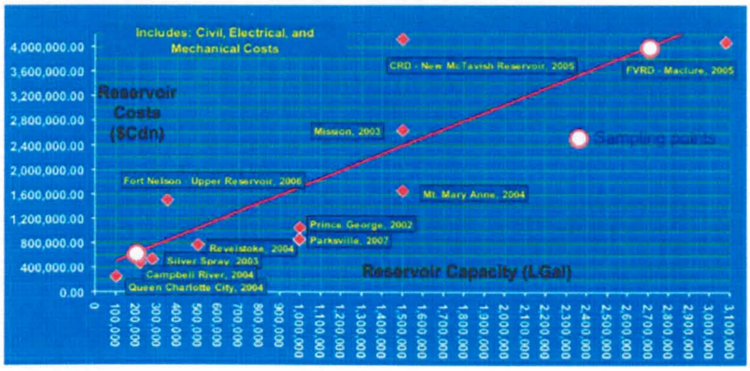

Figure 66: Expected cost of reservoirs

The line of best fit was given by the expression:

Cost of reservoir (£)= volume of reservoir (m^3) x 213.6 + 253,000 (£).

This relationship was used as the basis for the costs associated with reservoirs. The reservoir for each scenario was sized based on the maximum water storage required during the year, when the local population demands 85% of the maximum output (5950m^3/day)[67].

6.3.3 Reverse Osmosis Plant Costs

Cost estimates were published in the 'Newhaven Desalination Appraisal' [Nardin, 2003a], for a proposed seawater reverse osmosis plant at Newhaven, in 2003. The proposal was rejected on the basis that it was not the most cost-effective option, as reported in The Times [Brown, 2007]. The costs of the two No BSR RO plants of interest to this research, were estimated, with production capacities of 4,000m^3/day and 8,000m^3/day.

The capital costs of the RO process plants were £2.1M and £2.8M for the 4,000m^3/day and 8,000m^3/day plants, respectively, and the other auxiliary installations and works brought the total capital costs up to £5.94M and £6.78M, respectively.

These costs are shown in concise format below in Table 35.

---

[67] 85% of the required output represents the lowest acceptable level of consumption which would result in the largest reservoir capacity requirement for the RO plant in normal use.

Table 35: Edited costs from Newhaven Desalination Appraisal.

Capital costs	$4000m^3/day$ (£)	$8000m^3/day$ (£)
Reverse Osmosis process plant	$2.10x10^6$	$2.80\ x10^6$
Seawater intake system including low lift pumps.	400,000	431,000
Effluent outfall system	$2.17\ x10^6$	$2.17\ x10^6$
Electricity supplies	140,000	160,000
High lift pumps	20,000	40,000
Re-hardening plant	135,000	135,000
Civil works	310,000	380,000
Other miscellaneous equipment, engineering, studies, licences, etc.	664,000	664,000
Total	**$5.94\ x10^6$**	**$6.78\ x10^6$**

It is noteworthy that the reverse osmosis process plant itself only makes up around 35% – 40% of the total costs for the installation, and approximately the same amount is spent on the effluent outfall system. The total figures from Table 36 above were then plotted on a graph as shown below in Figure 67.

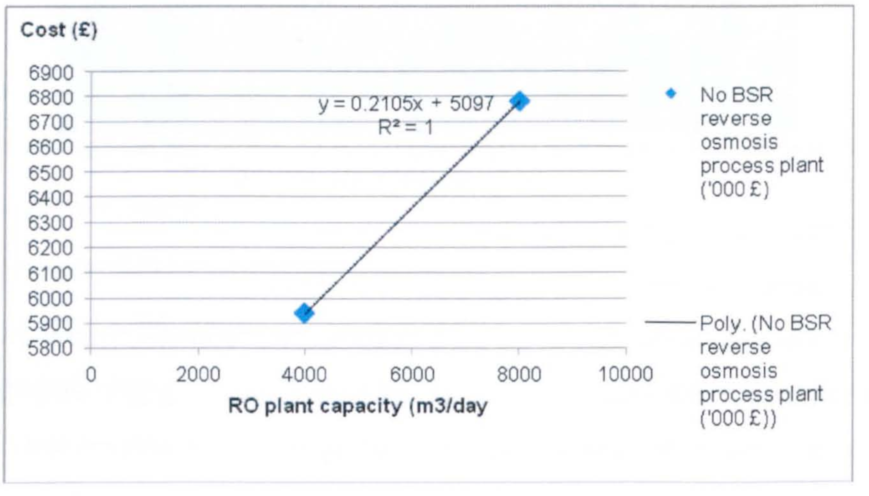

Figure 67: Cost of No BSR RO process plant

A straight-line graph was applied and the cost associated with a $7,000m^3/day$ plant was interpolated. This gave a capital cost for the No BSR plant of £6,570,500.

6.3.3.1 BSR Plants

For the purposes of this research, the capital costs associated with the BSR RO plants in comparison to the equivalent output No BSR RO plant were ascertained based on discussions with Daniel Shackleton[68], of Salt Separation Limited. He explained that the BSR options were not normally significantly more expensive than the No BSR RO plants, as the additional cost of the BSR equipment could be offset, to some degree, by the reduction in pumping capacity delivered by the increased efficiency of the system. The ratios of the costs was taken from the estimate for a $450m^3/day$ plant which would cost

[68] Director of Salt Separation Limited, on 9 November 2009. See website at http://www.saltsep.co.uk/ for greater details of Salt Separation Limited. [Last viewed on 7 August 2011].

£250,000,with an additional £30,000 (12%) and £50,000 (20%) for the Pelton Wheel and Pressure Exchanger BSR variants, respectively.

The estimated costs, if these smaller RO plants were simply scaled-up to produce 7,000m^3 per day, is shown below in Table 37.

Table 36: Cost of BSR and No BSR RO plants, based on scaled-up 450m^3/day plant.

Reverse osmosis plant type	Estimated RO plant cost (£x10^6) based on scaled-up 450m^3/day plant
No BSR	3.89
Pelton Wheel	4.36
Pressure Exchanger	4.67

The No BSR costs show a rise of around 36% against the cost of the 8,000m^3/day plant, which costs £2.8 million, as shown at Table 36 above.

Daniel Shackleton also explained that Pelton Wheels are sometimes used in RO plants designed to allow the Pelton Wheel system to be bypassed and run as a non BSR plant the event of failure. In this case of course, the BSR arrangements will be a full additional cost to the No BSR plant, as no offset due to reduced pumping capacity can be attributed.

The costs for the 7,000m^3/day reverse osmosis plants with and without BSR based on the Newhaven 2003 estimate are shown below in Table 37.

Table 37: Cost of BSR and No BSR RO plants based on 2003 estimates

Reverse osmosis plant type	Capital Cost (£x10^6)
No BSR	6.57
Pelton Wheel	7.36
Pressure Exchanger	7.88

6.3.3.1.1 Pressure Exchanger BSR RO plant cost

The data for a 50 Million gallons/day (189270m^3/day) Pressure Exchanger RO plant was obtained from Affordable Desalination – ADC[69], for the following recovery ratios:

- 35
- 42.5, and
- 50.

The costs associated with these recovery ratios were plotted graphically as shown below in Figure 68.

[69] The data for the Net Present Value costs were taken from http://www.affordabledesal.com/home/test_data.html on 14 January 2011 for an RO plant using the Filmtec SW30HR-380 membrane. [Last viewed on 7 August 2011].

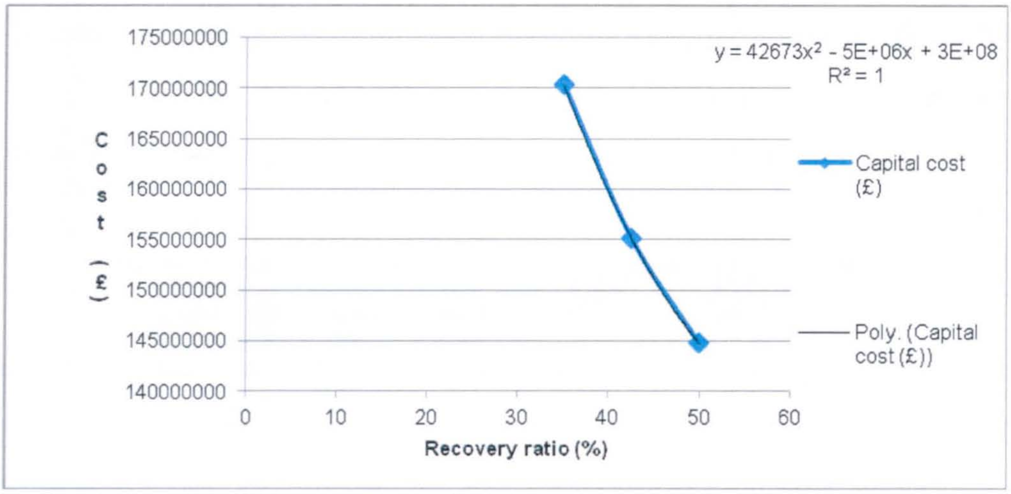

Figure 68: Cost of Pressure Exchanger BSR RO process plant, at various recovery ratios

The polynomial of the curve was extrapolated for a recovery ratio of 24% (which was the ratio associated with the maximum flowrate of the RO plants being modelled), and this gave a cost of over £204.5M. When this figure was interpolated for a 7,000m^3/day plant, it gave a cost of £7.57 million, which was relatively close to the 2003 cost for the Pressure Exchanger RO plant (£7.88 million) shown in Table 37 above.

6.3.3.2 Scrutiny of RO plant costs

The costs from Newhaven are estimates from 2003 and the ADC plant is very large and probably incorporates economies of scale. Therefore the costs estimated above are probably low.

A selection of RO plant costs in Florida based on 2006 figures is presented in 'Desalination in Florida', 'Estimated Costs to Build and Operate RO Desalination Facilities at Port Everglades, Lauderdale, and Fort Myers Power Plant Sites' [Division of Water Resource Management, 2010]. The document gives details of a Port Everglades Plant[70], which when scaled down from the presented scenario of 35million gallons/day (132489m^3/day), to 7,000 m^3/day gave a cost of £9.27M [Division of Water Resource Management, 2010]. This equates to an increase of just over 40% in 3 years, on the Newhaven 2003 estimated cost. This rise in costs is in keeping with the scaled-up RO plant costs at Table 37, and was discussed with William J. Conlon[71], and was considered reasonable to apply for 2010 costs.

[70] The Port Everglade's RO plant appears to be the best equivalent to base costs upon as it has water quality of 33,000mg/l of Total Dissolved Solids (TDS) in comparison to the modelled plants which have 27147.44mg/l, and the other plants where costs were available (Lauderdale and Fort Myers) have TDS levels of 15,000mg/l).

[71] William J. Conlon, P.E., BCEE, F.ASCE Technical Manager, Principal Professional Associate. Water Technical Excellence Center, Parsons Brinkerhoff Americas, Inc.

For the purposes of this research, the estimated costs shown below in Table 38 were employed, based on the expected rise in costs.

Table 38: Capital cost of BSR and No BSR RO plants

Reverse osmosis plant type	Capital Cost (£x10[6])
No BSR	9.27
Pelton Wheel	10.38
Pressure Exchanger	11.12

6.3.3.3 Operation and maintenance costs

The operation and maintenance costs were split into four main items:

- Membrane replacement
- Maintenance and Spares
- Labour, and
- Chemicals.

Of the four items above, chemical costs were the most difficult to assess. Table 39 below shows the chemicals expected to be employed, with approximate dosage rates and prices.

Table 39: RO plant chemical costs

Chemicals	Reason for use	Dosage		Cost/l	
		(g/m³)	(ml/m³)	(£/l)	(£/tonne)
Sulphuric acid 98%	pH adjustment	20		0.2	156
14% Sodium hypochlorite	Disinfection of drinking water	1.5	5.5		700
Ferric chloride	Used as flocculent to remove suspended materials	25			68.5
(Accepta 2651) Anti-scalant	**Added to the incoming feedwater to inhibit scaling on membranes**	**5**	**5**		**2270**
Accepta 20% Sodium Meta-bisulphate	**Used as membrane cleaning agent**	**10**		**0.75**	**750**
Sodium hydroxide	pH adjustment	20			197
Kalic[72] – 5.5% dose	**pH adjustment and acid neutralisation**				**6**
Carbon Dioxide	To increase hardness of permeate	130			102.3
Calcium chloride. 35% solution	For Calcium hardness in water adjustment	185			70
Sodium hydrogen carbonate (bicarbonate)	Pre-treatment. Used for pH adjustment	40			199

The data in **bold** was obtained from Philip Boswell of Accepta[73], and all other data was taken from the Newhaven Desalination Appraisal [Nardin, 2003b].

---

[72] Kalic liquid lime is a calcium hydroxide suspension.

[73] E-mail from Philip Boswell (International Technical Consultant) Accepta. See website at http://www.accepta.com/ for details of Accepta. [Last viewed on 7 August 2011].

The quantity and type of chemicals that need to be used will vary due to a variety of factors, including:

- Volume of feedwater due to varying recovery ratio
- Scaling on membranes
- pH of permeate

As such it is particularly difficult to attribute an accurate cost to a particular scenario.

This being the case, the RO plant chemical usage was approximated based on an average recovery ratio of 20%, giving 5 times the permeate volume as feedwater and 4 times the permeate volume as wastewater.

This gave an overall annual cost to produce 2,555,000m^3 over the course of one year (7,000m^3/day) as £306,240.

6.3.3.3.1 *Onsite spares*

The annual costs associated with onsite spares was taken as 10% of capital costs, based on discussions with Daniel Shackleton, who estimated that 5 – 10% should be allocated.

6.3.3.3.2 *Brine stream removal*

The costs associated with brine stream removal was taken as included within the capital cost of the No BSR and Pressure Exchanger BSR variants, but as an additional 10% of capital cost for the Pelton Wheel BSR RO plant.

6.3.3.3.3 *Annual operating costs of the BSR and No BSR RO plants*

The Annual operating costs for the BSR and no BSR RO plants are shown below in Table 40.

Table 40: Annual operating costs for the BSR and No BSR RO plants

Annual operating costs	No BSR (£)	Pelton Wheel BSR (£)	Pressure Exchanger BSR (£)
Membrane replacement[74]	34,200	34,200	34,200
Chemicals	306,240	306,240	306,240
Labour[75]	182,500	182,500	182,500
Maintenance and spares*	131,410	147,180	157,692
Onsite spares	927,066	1,038,314	1,112,479
Brine stream removal	0	1,038,314	0
Total (£x10^6)	1.581	2.747	1.793
Operating cost (£/m^3)	**0.62**	**1.08**	**0.70**

* The estimated costs for maintenance and spares was taken as 2% of capital cost per year based on 'The feasibility analysis of RO systems' [Atikol, 2005].

6.3.3.4 Life time costs of RO plants

Based on the assumption that the RO plants will have a 25-year life, the RO plant costs shown in Table 41 were employed for the modelling exercise.

Table 41: Life time costs for the BSR and No BSR RO plants

No BSR (£)	Pelton Wheel BSR (£)	Pressure Exchanger BSR (£)
48,806,060	79,051,840	55,952,572

[74]The membranes employed for this exercise were Filmtec SW30HR-320 membranes, but these are no longer available, so the costs for the RO plants are based on the Filmtec SW30HR-380. The Filmtec SW30HR-380 varies from the Filmtec SW30HR-320 in that the product water flowrate for the HR-380 is 950l/hr and for the HR-320 is 790l/h. This is based on Table 1 of 'Mature and novel desalination experiences with the FILMTEC SW30HR-380 and SW30HR-320 elements Technical-economical review' by J.A. Redondo and A. Casañas, which was published in Desalination 125 (1999), Article 1 of 8, available at http://www.desline.com/articoli/3738.pdf. [Last viewed on 7 August 2011]. The cost of the SW30HR-380 is quoted as £600 each by Nicola Ramsden of Desal Supplies Ltd. The modelled facility has 284 membranes (142 pairs) so, on a rolling 5-year replacement cycle, 1/5th of the membranes (57 membranes) would be changed each year, which would cost £34,200/year.

[75] For the purposes of this model, it is assumed that all the plant types (BSR and No BSR options) would require full-time support, if short-notice switching was required due to frequent stopping and starting of the plant due to the variable power inputs from the renewable energy sources. This is estimated at a flat rate of £500/ day (for two trained technicians to provide 24-hour cover) for all plant types.

6.3.4 Scaling-up scenarios to make them competent

There was limited success in identifying technically-competent scenarios that were able to meet the water demands of the local population due to the impact of intermittency, but it was clear that if the scenarios were scaled-up (extrapolated), competent scenarios could be identified where the full demand of the local water users could be met.

Note: It is assumed that the reservoir starts empty at the start of the modelled year, and the conventionally-powered RO plant is capable of meeting the user demand if the model is started at midnight.

6.3.4.1 Extrapolations considered

Three extrapolations of the modelling were considered to identify competent scenarios:

1. Increasing the size of the RO plant, and therefore output of the RO plant, to enable the excess power (normally wasted when the RO plant is of normal size) to be used.
2. Increasing the size of power installation to allow the RO plant to run continuously.
3. Increasing the RO plant and Power plant by the ratio of water shortfall, i.e. if a given RO plant and Power plant scenario makes 50% of required water, both RO plant and installed power are doubled in size.

6.3.4.2 Extrapolation employed

The method adopted was to increase the size of both the RO and installed power plant, in equal proportion.

Individual plant scaling (of RO plant and Power plant) methodologies were considered but were not pursued, due to time constraints. It is considered that there is merit in refining the scale-up methodology as a part of any further work.

6.3.4.2.1 Simple scale-up methodology

This scale-up methodology (although the most simple to employ) does not take account of the constant water abstraction rate of the local users. As such, the scale-up:

- May produce 100% of the water demanded over the course of the year, but
- May not produce it at the times during the year when the local population are demanding it.

Also, the scale-up includes the scale-up of the reservoir by the same ratio. As can be seen in Figure 69 below, which shows how the reservoir size increases in relation to water production. The scenarios that did not produce significant amounts of water had very small reservoirs, and once scaled-up still had relatively small reservoirs, i.e. scaling up a scenario that originally produced 50% of the water by two times, would not give the correct size of reservoir for the scenario that now produces 100% of the water required.

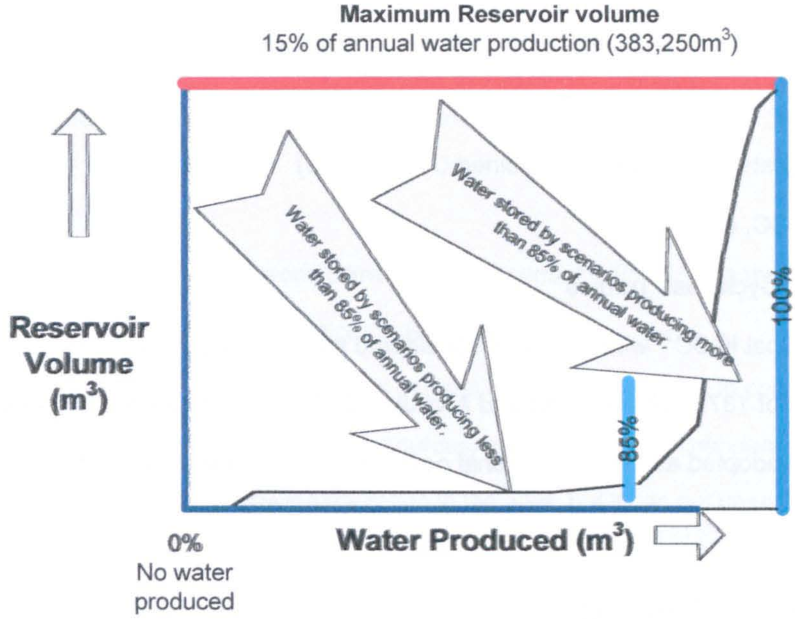

Figure 69: Illustration of reservoir size to water production: Not to Scale.

To manage this discrepancy, each scaled-up scenario had the reservoir priced as holding 15% of the annual production of a plant that produces 100% of the annual water required (2,555,000m^3). 15% is taken as 383,250m^3 at the end of the year. This equates to a reservoir costing £82,115,200.

6.3.5 **Conventional power costs**

To obtain an absolute measure of the financial viability of renewable power, a cost comparison must be made against the most reasonable alternative that it will displace. Therefore, the section below presents the estimated costs of the most probable conventional power sources at Newhaven and Massawa that the renewable power scenarios must be competitive with, to be considered financially viable.

6.3.5.1 Newhaven

Following the UK Budget of 22 April 2009, the UK Government announced the following measures to encourage Carbon Capture and Storage (CCS) development within the UK:

> *"No new coal-fired plant without CCS demonstration from day one."*
>
> *"Full scale retrofit of CCS within five years of the technology being independently judged as technically and commercially proven."*

Therefore it was considered probable that CCS would be employed in the UK, and that coal would be a major source of energy (within the grid mix of energy sources) to power the proposed RO plant.

For the purpose of this research, it was assumed that the power to operate the RO plant at Newhaven would be provided by a large coal-fired plant, and that costs for CCS would be based on the portion of the plant's output consumed to operate the RO plant (i.e. that the RO plant would not have a dedicated coal fired CCS power station).

CASES [Blesl, 2008] makes estimates of three variants of energy generation with coal incorporating CCS:

- Coal Integrated Gasification Combined Cycle (IGCC)
- Lignite IGCC, and
- Combined Cycle Gas Turbine

Of these options, Coal IGCC[76] with CCS was considered the most likely option, as the UK has potential hard coal reserves of 187,000Mt [Cramer and Andruleit, 2009] (but only limited reserves of lignite and gas). So, coal was adopted as the conventional power source at Newhaven for the renewable models to be compared with.

6.3.5.1.1 *Estimated costs of CCS.*

There are a variety of reports that give estimated costs for CCS and these provide a significant range of results. The lowest estimated costs [Bauer, 2008] are given in Table 42 below.

Table 42: Lowest estimated costs associated with CCS

Investment cost (€/kW)	Fixed €/kW/A	Variable O&M Costs (€/MWh)
1370	65	3.6

The 'Power Engineering Magazine' article 'IGCC cost wrap' [Power Engineering, 2010][77], quotes:

'*IGCC power plant project costs top $5,500/kW*',

and another planned IGCC plant, with CCS, in North America costing around $5,800/kW (around £3,700/kW).

6.3.5.1.2 *CCS cost estimate used.*

For the purposes of this research, a coal-fired power station with CCS was modelled with costs as shown in Table 43 below.

---

[76] The integrated gasification combined cycle (IGCC) is a technology that turns coal into synthesis gas (syngas). It then removes impurities from the gas before it is combusted and attempts to turn any pollutants into re-usable by products. This results in lower emissions of sulphur dioxide, particulates and mercury. Excess heat from the primary combustion and generation is then passed to a steam cycle, where a second stage of generation occurs which improves efficiency, compared to conventional pulverized coal. Further details of the cycle are available at the IGCC International Energy Association (IEA) web page at http://www.iea-coal.org.uk/site/ieacoal_old/clean-coal-technologies-pages/clean-coal-technologies-integrated-gasification-combined-cycle-igcc? [Last viewed on 7 August 2011].

[77] It is noteworthy that the plants discussed are very large (582MW and 602MW) and are designed to burn lignite.

Table 43: CCS cost estimates employed in this research.

Investment cost ($/kW)	Investment cost (£/kW)	Fixed O&M costs[78] £/kW/A	Variable O&M Costs[79] (£/MWh)
3384	2152	41.42	83.95

These values were based on 'The Strategic Analysis of the Global Status of Carbon Capture and Storage Report 2' [Worley Parsons, 2009], which provided a very comprehensive overview of the costs associated with CCS. The values lie in between the two extremes presented earlier.

6.3.5.2 Massawa

Eritreans are reported to have one of the world's lowest energy consumption rates in the world with its electricity consumption ranked 179 out of 215 globally [CIA, 2012].

Eritrea itself has approximately 60 MW of diesel-fired generating capacity, but due to economic reasons[80], does not have any of its own fossil fuel resources, making it totally dependant on imports of fossil fuels. There is a history of hydrocarbon exploration in the area, but it has not been particularly successful[81].

It was intended that additional electrical generating capacity be installed near Massawa, but work is still ongoing to fully integrate the facility with the rest of Eritrea.

There is power available at Massawa from the existing power supplies at Hirgigo[82], but for the purposes of this research it was assumed that dedicated diesel generators were employed to provide the power to operate the RO plants.

---

[78] Derived from cost of $45,203 per annum for an IGCC plant with CCS with 694MW generating capacity, giving a specific value of $65.134/MW.

[79] This total is made up of:

- Generation and Capture of CO_2 – $121/MWh
- Transportation of CO_2 - $4/MWh
- Storage of CO_2 - $6/MWh
-

[80] Until it closed in August 1997, the Assab refinery supplied refined product for consumption in Eritrea and neighbouring Ethiopia (which part-owned the refinery, via the Ethiopian Petroleum Corporation). Due to high operating costs, the refinery was closed in 1997, with both countries agreeing to import petroleum products for at least 10 years.

[81] Hydrocarbon exploration, primarily offshore in the Red Sea, began in the 1960s when Eritrea was still federated with Ethiopia. In 1995, Eritrea signed a production sharing contract (PSC) with U.S.-based Anadarko Petroleum for the offshore Zula Block. Anadarko signed a second PSC for the offshore Edd Block, located south of the Zula Block, in September 1997. Anadarko announced, in December 1997, that it had reached an agreement with ENI/Agip to swap interests in exploration acreage. Anadarko received a 25% interest in a Tunisian block operated by Agip, and Agip received a 30% share in the 6.7-million acre Zula Block and 30% interest in the Edd Block. Burlington Resources, a U.S.-based independent, later joined the consortium by acquiring a 20% interest in both acreages. Anadarko's first two exploration wells, both drilled on the Zula Block, were unsuccessful. In January 1999, a third dry well, Edd-1 on the Edd Block, was drilled. Citing the disappointing exploration results, Anadarko and its partners ceased exploration activities and relinquished their rights to the offshore blocks.

[82] In 1997, South Korean firms Daewoo and Hanjung signed an agreement to build a heavy oil-fired plant in at Hirgigo, (around 9 km from Massawa) but this work has not been completed. The plant, when nearly completed, was damaged in a bombing raid by Ethiopia in 2000. In 2001, Eritrea signed loan agreements with the United Arab Emirates and Saudi Arabia for the facility's repair.
The 88 MW facility (more than twice the existing capacity in Eritrea) came online in March 2003, but many industry experts fear that the new capacity could overload Eritrea's dated grid system. Both the European Development Fund and the World Bank have considered projects to update the transmission lines, but firm contracts have not been negotiated.

6.3.5.2.1 *Costs associated with diesel power generation*

Cost details to be employed at Massawa were kindly provided by Mike Gabriel of Power Electrics (Bristol)[83] and are shown below in Table 44.

Table 44: Costs associated with power generation by diesel generator

RO Plant	Power required (kW)	Diesel generator power rating (kVA)[84]	Cost for diesel generator and auxiliaries[85] (£x10^5)	Maintenance[86] (£)
No BSR	2400	3000	3.80	1,600.00
Pelton Wheel BSR	1000	1250	1.60	1,100.00
Pressure Exchanger BSR	800	1000	1.25	900.00

6.3.5.3 Cost of running RO plants at Massawa and Newhaven.

6.3.5.3.1 *Massawa*

The diesel generator fuel consumption was derived based on the fuel required to maintain the average power use over the course of the year for the RO Plant scenarios.

The following are details for each scenario, with the data shown below in Table 45:

- The greatest power demanded during the year
- The power installed (it is assumed that only 80% of the power generated is usable due to the power factor of 0.8)
- The average power consumption by the RO plant to ensure the correct volume of water is produced over the course of one year
- The average power generation required (taking the 0.8 power factor into account).

Table 45: Average power generation required at Massawa for each RO plant modelled.

Type of RO plant	Greatest power demand by RO plant during year (MW)	Diesel generator power installed (MW)	Average level of power consumed by RO plant during year (MW)	Average level of power generated by diesel generator (MW)
No BSR	2.33	3.00	2008	2.51
Pelton Wheel	0.99	1.25	869	1.09
Pressure Exchanger	0.77	1.00	657	0.82

---

[83] See http://www.power-electrics.co.uk/ [Last viewed on 7 August 2011] for greater detail of power electrics organisation.

[84] Diesel generators modelled have a power factor of 0.8 lagging which is the standard power factor. The power factor is the ratio of watts (true power) to VA (volt-amperes, also called apparent power) generated. Where the load is reactive (capacitive or inductive), it stores energy, releasing it during a different part of the cycle, which moves the current cycle waveform so that it is offset, or out of phase with the voltage cycle waveform. In practical terms, a power factor of 0.8 lagging means that only 80% of the power produced by the diesel generator is available for the RO plant to use, so the installed power and power produced by the diesel generator must be 25% greater to compensate for this.

[85] Prices include a container to limit external noise to 80dBa at 1 metre, and a 72-hour capacity bulk fuel tank.

[86] Maintenance costs were taken to involve 2 visits per year for an A and a B service. It was taken that the service provider would be located locally and thus travelling expenses not incurred.

The volume of diesel fuel required to maintain this level of power over the course of one year was derived using an 'Approximate Diesel Fuel Consumption Chart' [Diesel Service and Supply, 2011]. The data on this chart gave full load consumption for generators of various sizes, based on kW_{el} output. The fuel consumption for each generator size was quoted in US gallons/ hour, which was then converted to litres/ year by multiplying by 33200[87].

When the cost of the diesel fuel in Eritrea from GIZ in 2011 [Wagner, 2011] ($1.07/ £0.68 per litre) and was incorporated, it gave the relationship shown below in Figure 70 between fuel cost and generator size. It is also noteworthy that at the time of drafting Eritrea had the most expensive petrol in the world at £1.615 per litre.

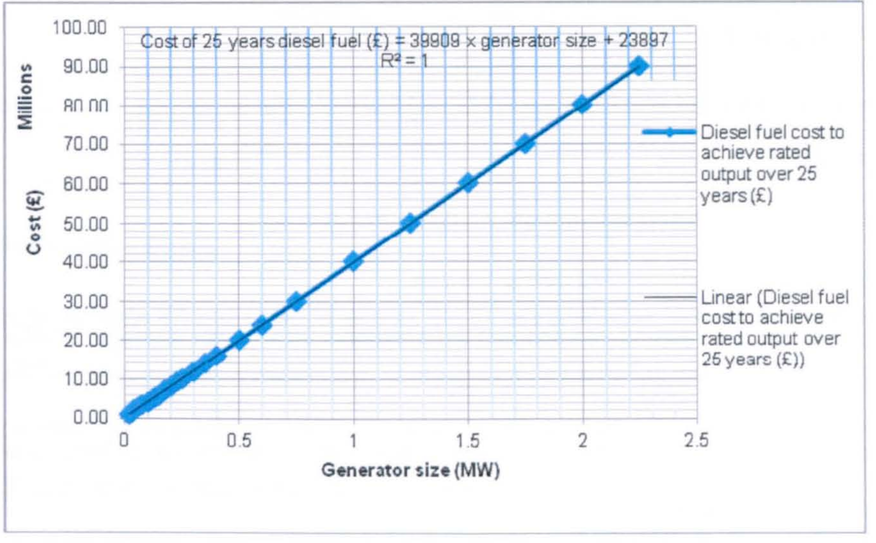

Figure 70: Fuel cost at Massawa during one year for varying generator sizes.

The fuel costs to maintain the average power generated for each RO plant scenario (shown above in Table 46) was derived using this relationship.

This resulted in the diesel generator costs shown below in Table 46 for the 25-year life of the installation.

Table 46: Average power generation required at Massawa for each RO plant modelled.

Type of RO plant	Installed power costs (£)	Fixed O&M costs (£)	Fuel cost for 25 years of water production (£x10^6)
No BSR	380000	40000	100.2
Pelton Wheel BSR	160000	27500	43.4
Pressure Exchanger BSR	125000	22500	32.8

The estimated costs associated with water production at Massawa using diesel generators is shown below in Table 47.

[87] 1 US gallon = 3.79 litres, so 3.79 x 8760 (the number of hours in one year) = 33200 converts US gallons/ hour to litres/ year.

Table 47: Full scenario costs for water production using diesel generators, at Massawa

RO Plant	Total costs for installed power over 25 years (£x10^6)	Total cost of RO plant over 25 years (£x10^6)	Cost of reservoir (£x10^6)	Total cost of Scenario over 25 years (£x10^6)
No BSR	100.6	48.81	82.2	232
Pelton Wheel BSR	43.6	79.05	82.2	205
Pressure Exchanger BSR	33.0	55.95	82.2	171

It is noteworthy that the No BSR scenario is around 1.1 and 1.4 times as expensive as the Pelton Wheel and Pressure Exchanger scenarios, respectively. This is mainly due to the cost of the diesel fuel, which makes up just over 43% of the total lifetime costs for the No BSR scenario, in comparison to around 20% for the BSR scenarios.

6.3.5.3.2 Newhaven

The cost of the coal-fired plant with CCS, were derived based on the power used over the course of the year, for the RO Plant scenarios.

The following details for each scenario are shown below in Table 48:

- The greatest power demanded during the year
- The power installed (taking into account the additional 30% power required for on site capture and compression of CO_2)
- The power consumption by the RO plant to ensure the correct volume of water is produced over the course of one year
- The average power generation required (taking into account the additional 30% power required for on site capture and compression of CO_2).

A Report on 'The energy penalty of post-combustion CO_2 capture & storage and its implications for retrofitting the U.S. installed base' [House et al, 2009] states that there is an absolute lower bound for the energy penalty [additional energy required for on-site CO_2 capture and storage] of 11% of the power produced, and that an energy penalty of 40% can easily be reached. An energy penalty of 29% represents a decent target value. Based on these findings, an energy penalty of 30% was adopted for this research, although it is noteworthy that this energy penalty is expected to reduce to below 10% for plants commissioned after 2020 [Florin and Fennel, 2010].

Table 48: Power generation required at Newhaven for each RO plant modelled.

Type of RO plant	Greatest power demand by RO plant during year (MW)	Power installed with Coal-fired plant with CCS (MW)	Power consumed by RO plant during year. (MWhx10^3)	Power generated by Coal-fired plant with CCS (MWhx10^3)
No BSR	3.33	4.4	31.7	41.3
Pelton Wheel BSR	1.31	1.8	12.9	16.8
Pressure Exchanger BSR	1.06	1.4	10.2	13.3

This resulted in the operating costs of the coal-fired plant with CCS shown below in Table 49.

Table 49: Power generation costs at Newhaven for each RO plant modelled.

Type of RO plant	Installed power costs ($£x10^6$)	Fixed O&M costs ($£x10^6$)	Variable O&M cost for 25 years of water production ($£x10^6$)
No BSR	9.5	4.6	66.7
Pelton Wheel	3.9	1.9	27.0
Pressure Exchanger	3.1	1.5	21.4

The estimated costs associated with power production at Newhaven using coal-fired plant with CCS are shown below in Table 50 for the 25-year life of the installation.

Table 50: Full scenario cost for water production using coal fired plant with CCS at Newhaven

	Total costs for installed power ($£x10^6$)	Total cost of RO plant ($£x10^6$)	Cost of reservoir ($£x10^6$)	Total cost of Scenario ($£x10^6$)
No BSR	80.7	48.81	82.21	211.7
Pelton Wheel BSR	32.8	79.05	82.21	194.06
Pressure Exchanger BSR	26.0	55.95	82.21	164.15

6.3.5.3.3 The relative costs

As can be seen from Table 47 and Table 50 above, the initial installation costs of the Newhaven coal-fired plant with CCS, were relatively expensive, at around 24 times that of the diesel generator system at Massawa. Then, throughout the life of the plant, the variable costs associated with the operation of the Newhaven CCS plant come to less than 40% of the diesel fuel costs at Massawa for all the RO plant scenarios. As a result, with all other costs being unchanged (reservoir, RO plant, etc), the diesel generator scenario at Massawa finishes around 8.5% and around 5% more expensive than the Newhaven coal-fired plant, for the No BSR and BSR RO plant scenarios, respectively at the end of the 25-year life of the installation.

6.4 Comparison of technically-competent renewable energy-powered scenarios with conventionally-powered scenarios

The following section presents the costs of the scaled-up (technically-competent) renewable energy scenarios in comparison to cost of conventionally-powered scenarios, at each site, for each of the RO plant types modelled.

In the following Figures, the cost comparison with the conventionally-powered scenario is the y-axis, and '1' on the y-axis is the estimated cost for the conventionally-powered scenario. The estimated cost of the renewable energy powered scenario must be equal to, or less than 1, to be financially viable.

The most financially-attractive scenarios for each stage and/ or RO plant type, are identified by data tabs as appropriate. These data tabs are read as follows:

X: indicates the primary power installed for the scenario

Y: indicates the ratio against the conventionally powered scenario

Z: indicates the secondary power installed for the scenario, as appropriate.

6.4.1 Stage 1 – RO plant with No Brine Stream Recovery.

6.4.1.1 Massawa

As can be seen from Figure 71 below, the cheapest option when using only solar power to operate the No BSR RO plant at Massawa is just under 1.5x the estimated cost associated with using a diesel. The solar-based system is estimated to require 37210kW of solar power for an RO plant with 18619m^3/day capacity.

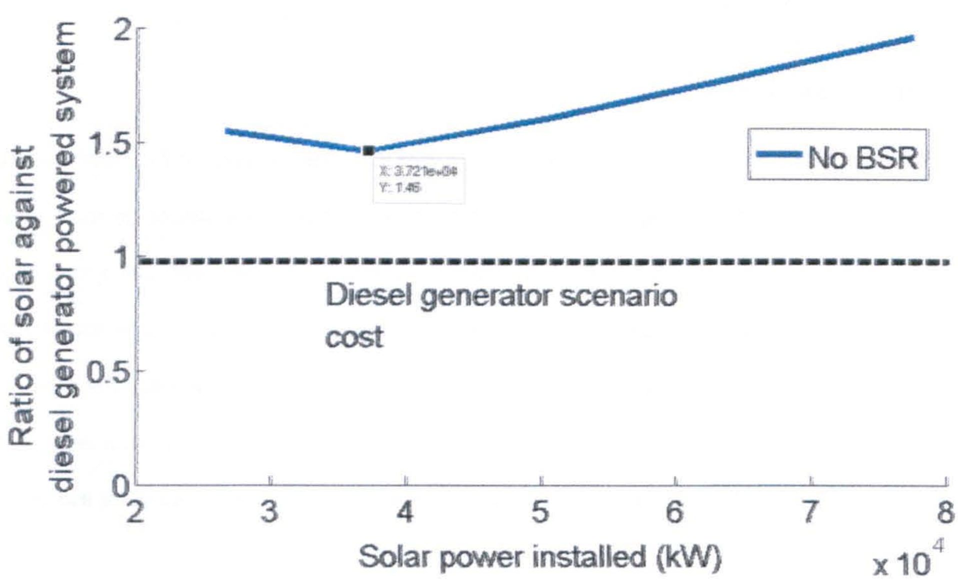

Figure 71: Cost ratio of solar power against diesel generator powered system, for varying solar power installed, for No BSR plant at Massawa.

The most financially-attractive scenario for Massawa is not intuitive, in that it does not use the smallest amount of installed power. This is due to the scale-up methodology employed (as explained at section 6.3.4), which uses a scale-up factor, which varies according to the amount of water produced from the original modelled scenario.

As can be seen in Figure 72 below, the originally modelled scenario water production increased most rapidly between 1x and 2x installed power, which increased the water produced by over 11%.

The next 3 increases in installed power only increased the water produced by a further 7.5%.

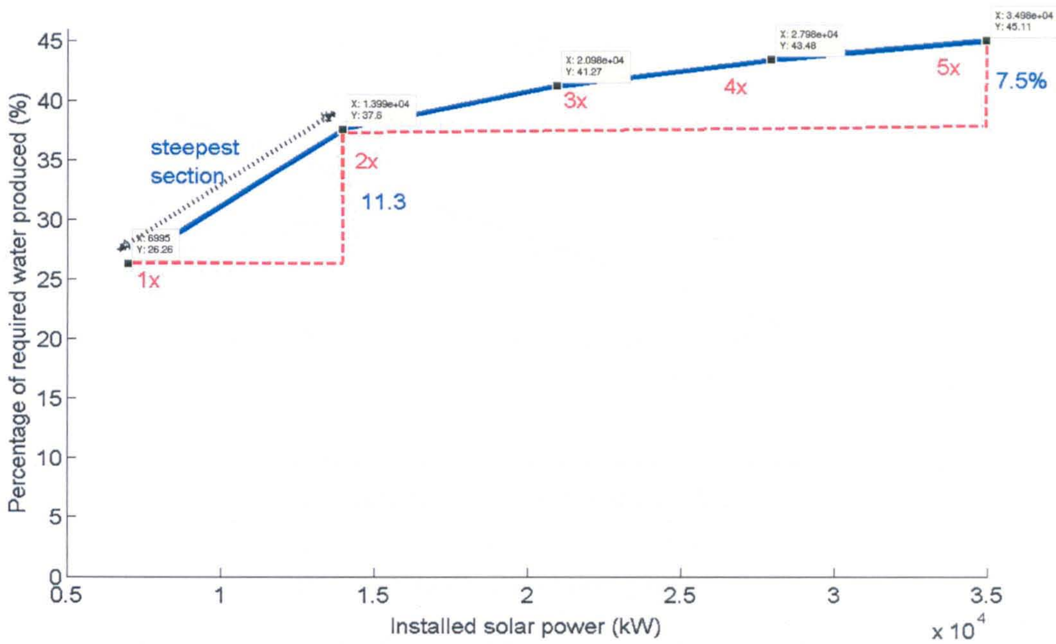

Figure 72: Water produced using solar power only

This reduced effectiveness of installed power to make water is due to the fact that most of the additional power provided is beyond the maximum that the RO plant can utilise as explained at section 5.1.1. The limited increase in water production at higher installed power is achieved mainly by extending the duration of production, at the cost of increasing the proportion of power wasted.

When a scenario is scaled up, there is a cost impact due to the increase in installed power and RO plant size, as the Reservoir costs remain constant. The components (installed power, RO plant and reservoir) that make up Figure 71 are shown below in Figure 73.

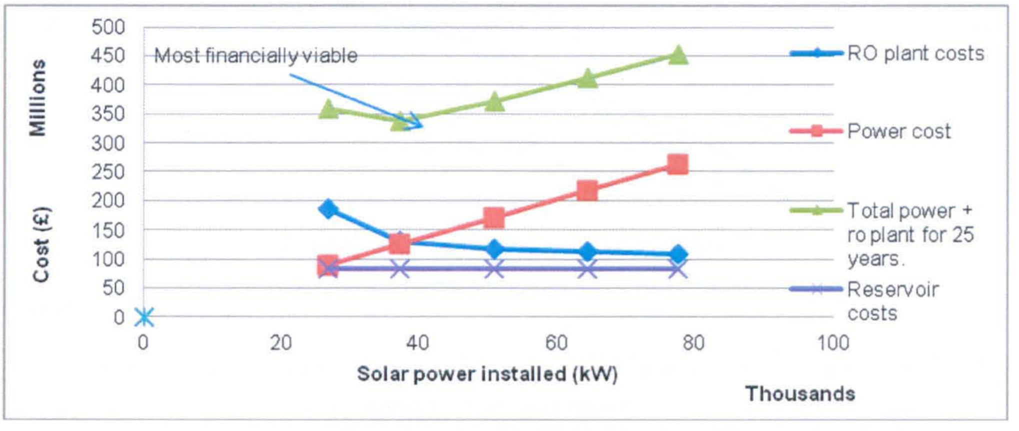

Figure 73: Solar scenario cost components

6.4.1.2 Newhaven

As can be seen in Figure 74 below, the cheapest option when using tidal current power to operate the No BSR RO plant at Newhaven, is just under 3x the estimated cost associated with using a coal-fired plant with CCS to provide the power. The tidal current-based system is estimated to require 135300kW of tidal current power to be installed for an RO plant with 28367m^3/day capacity.

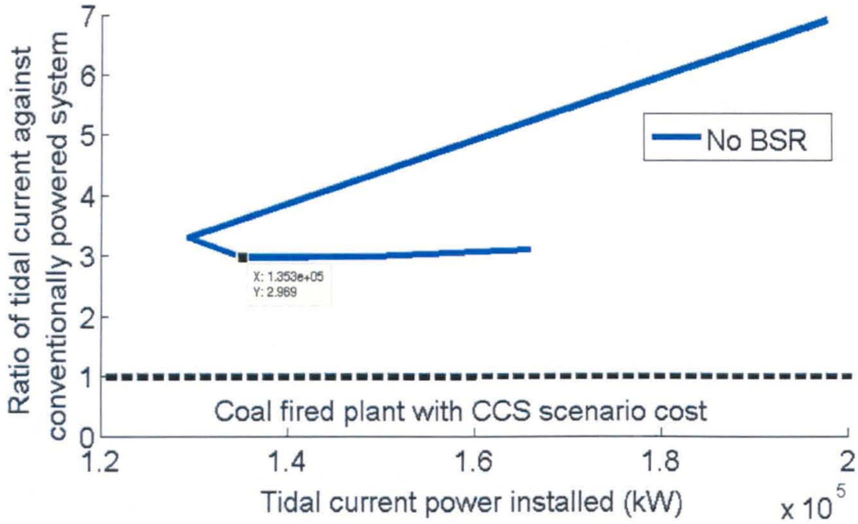

Figure 74: Cost ratio of tidal current power against coal-fired plant with CCS, for No BSR Plant at Newhaven.

As with Massawa, the most financially attractive scenario for Newhaven is not intuitive, in that it does not use the lowest amount of installed power. This is due to the scale-up methodology employed (as explained at section 6.3.4), which uses a scale-up factor, which varies according to the amount of water produced from the original modelled scenario.

As can be seen in Figure 75 below, the scale-up factors (shown in red) vary considerably as the scenarios produced increasing amounts of water.

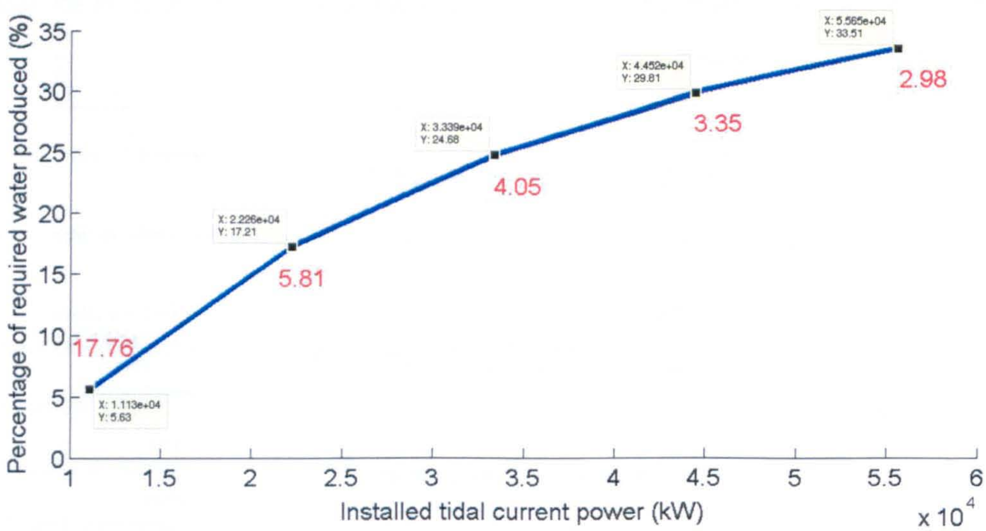

Figure 75: Water produced and associated scale-up factor, using tidal current power only

The application of these scale-up factors resulted in increases of installed power as shown in Figure 76 below.

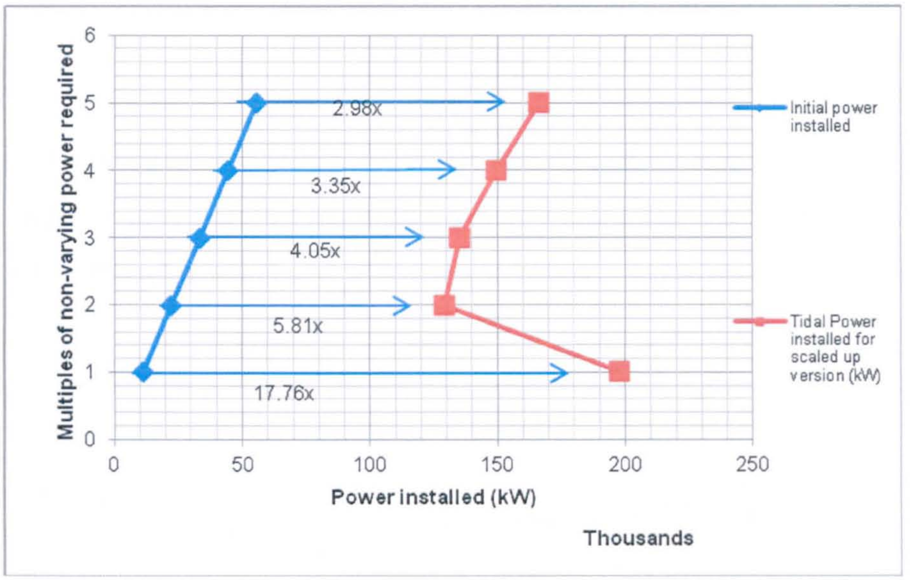

Figure 76: Impact of scale up factors on installed power

When each scenario is scaled up, there is a cost impact due to the increase in installed power capacity and RO plant size (as the Reservoir costs remain constant- see section 5.1.1 for explanation). The components (installed power, RO plant and reservoir) that make up Figure 74 are shown below in Figure 77.

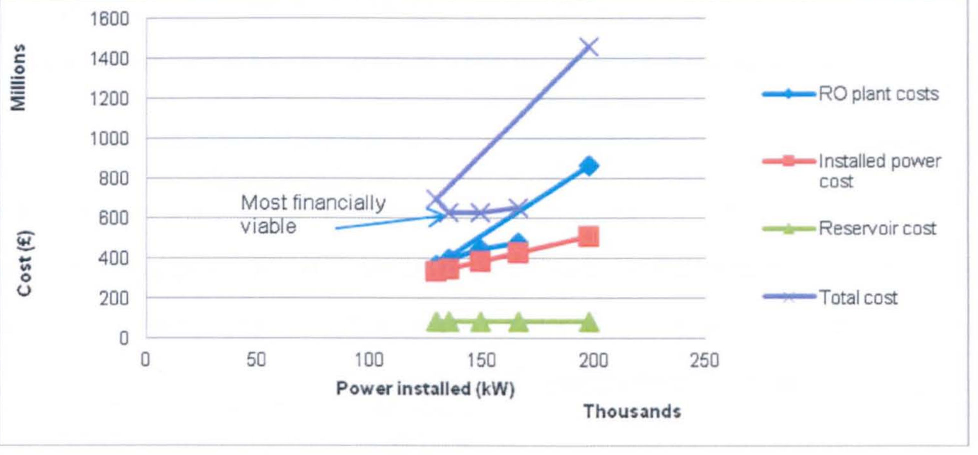

Figure 77: Tidal current scenario cost components

6.4.1.3 Conclusion

None of the scenarios modelled that employed only solar power at Massawa or tidal current power at Newhaven, were financially viable on a cost basis with conventionally-powered scenarios.

6.4.2 **Stage 2 – RO plants with Brine Stream Recovery.**

6.4.2.1 Massawa

As can be seen in Figure 78 below, the cheapest BSR option when using solar power at Massawa, is just under 1.65x the estimated cost associated with using a diesel generator to provide the power. The solar-based system is estimated to require 17440kW of solar power, for a Pressure Exchanger BSR RO plant with 17451m^3/day capacity.

None of the BSR RO plants modelled were financially viable when operated with only solar power.

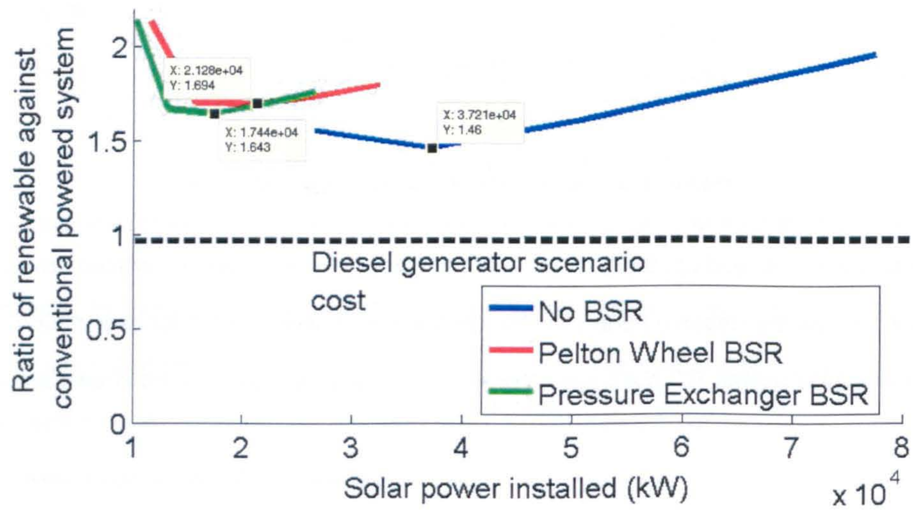

Figure 78: Cost ratio of solar powered system against diesel generator powered system, for BSR and No BSR RO Plants at Massawa.

6.4.2.2 Newhaven

As can be seen from Figure 79 below, the cheapest option when using tidal current power to operate RO plants at Newhaven, is just under 2.47x the estimated cost associated with using a coal-fired plant with CCS. The tidal power-based system is estimated to require 54380kW of tidal current power for a Pressure Exchanger BSR RO plant with 22801m^3/day capacity.

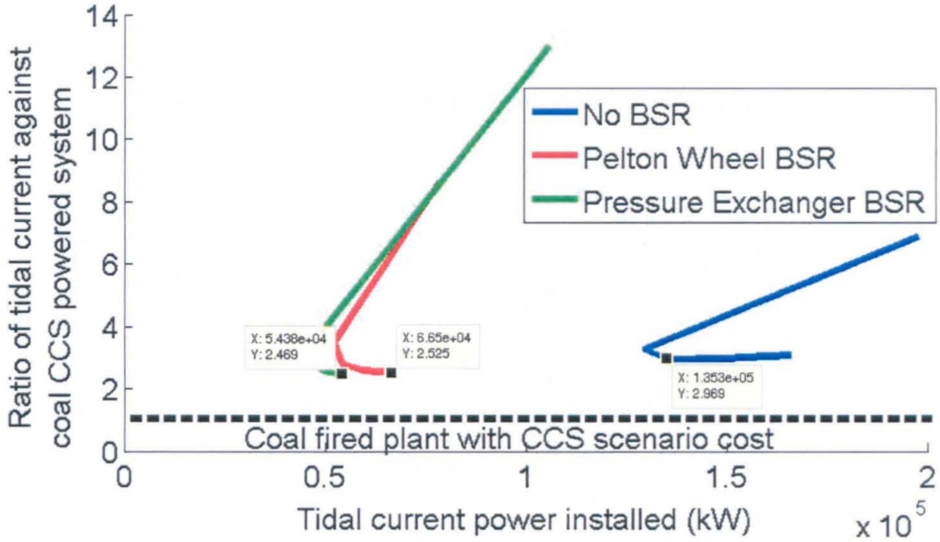

Figure 79: Cost ratio of tidal current power against coal-fired plant with CCS, for BSR and No BSR RO Plants

6.4.2.3 Comparison of the two sites

Presented in Figure 80 below are Figure 78 and Figure 79 on the same axis for direct comparison. As can be seen in Figure 80 below, the Massawa scenarios are significantly more financially attractive than any of those at Newhaven, with all plant types being cheaper at Massawa than the cheapest at Newhaven.

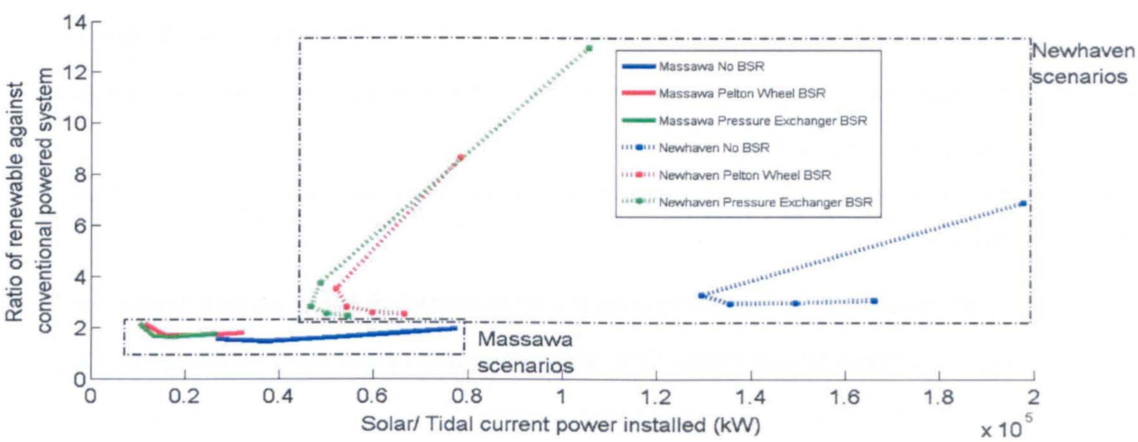

Figure 80: Cost ratio of Renewable Energy-powered systems against conventional, for BSR and No BSR RO Plants at Massawa and Newhaven

6.4.2.4 Conclusion

None of the BSR scenarios were financially viable on a cost basis with conventional powered scenarios.

6.4.3 Stage 3 – The addition of wind or wave power.

The comparisons for stage 3 are presented in terms of the addition of wind or wave at each site.

The example of solar and wind powered scenarios at Massawa using the full set of cost comparison results is shown below in Figure 81. This provides an indication of the expected spread of scenario costs in comparison to the diesel scenario between the most and least expensive scenarios.

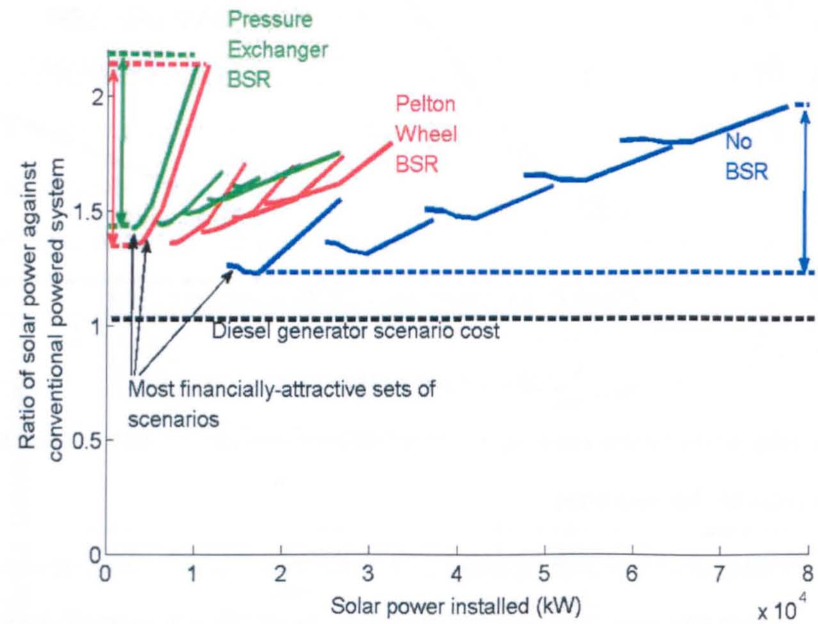

Figure 81: Cost ratio of scenarios using solar power supplemented with wind power, against diesel powered system, for BSR and No BSR RO Plants at Massawa

Although it can be seen that there is an appreciable spread of costs for the different scenarios using a combination of solar and wind power, the objective of the presentation of these results is to identify the most financially-attractive scenarios. So for clarity, only the most financially-attractive sets of scenarios are shown in the diagrams in the following section. In Figure 81 above, the most financially-attractive options are shown by the black arrows.

6.4.3.1.1 Massawa

The most financially-attractive cost comparisons for the addition of wind/ wave power are presented below for Massawa, in Figure 82 and Figure 83 for the addition of wind and wave power, respectively.

Addition of wind power

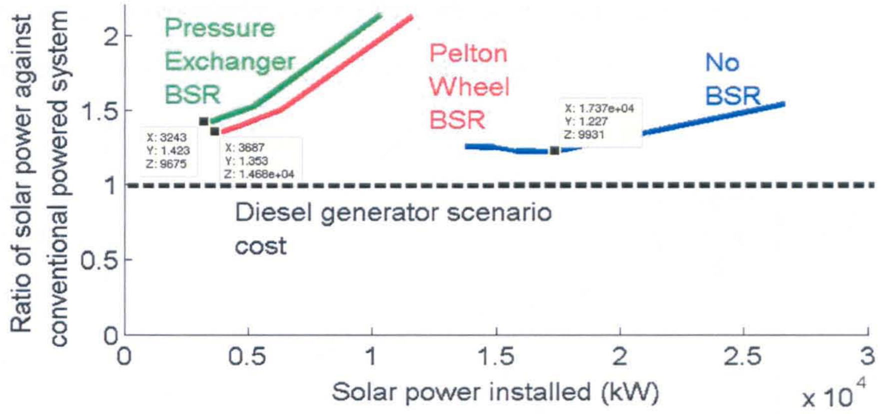

Figure 82: Cost ratio of most financially attractive of scenarios using solar power supplemented with wind power, against diesel powered system, for BSR and No BSR RO Plants at Massawa

Addition of wave power

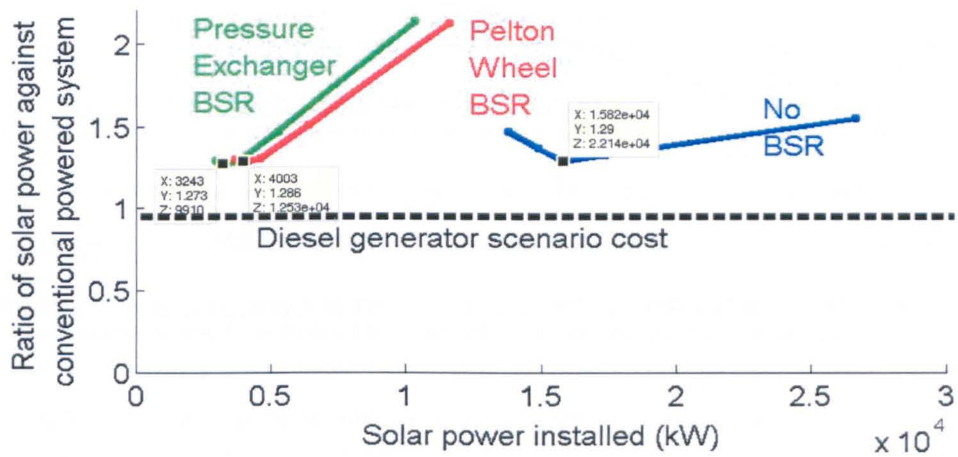

Figure 83: Cost ratio of most financially attractive scenarios using solar power supplemented with wave power, against diesel powered system, for BSR and No BSR RO Plants at Massawa.

As can be seen from Figure 82 and Figure 83 above, none of the options modelled were found to be financially viable. The addition of wind power to the No BSR scenarios was slightly more effective on a cost basis, than the addition of wave power, but the addition of wave power resulted in the most favourable scenarios for the BSR RO plants. The most financially-attractive scenario for the addition of wind/ wave was the No BSR RO plant powered by solar and wind energy, with a ratio of just under 1.3x the estimated cost associated with using a diesel generator to provide the power.

This system was estimated to require 17380kW of solar power and 9931kW of wind power (27311kW in total) for a No BSR RO plant with 17380m^3/day capacity.

6.4.3.1.2 Newhaven

The most financially-attractive cost comparisons for the addition of wind/ wave power is presented for Newhaven below in Figure 84 and Figure 85, for the addition of wind and wave power, respectively.

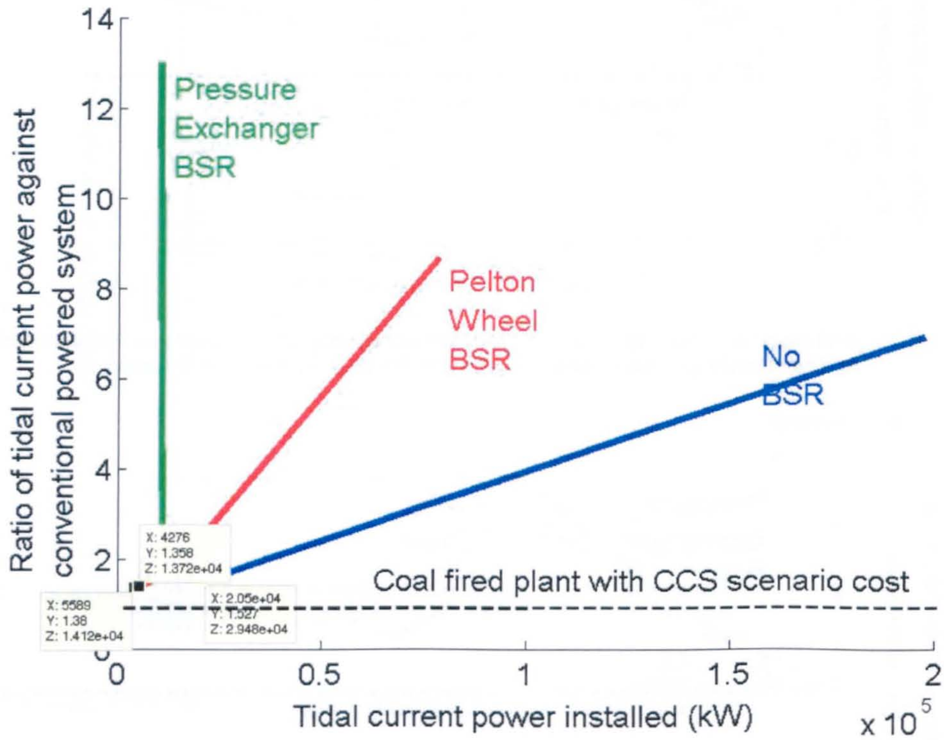

Figure 84: Cost ratio of most financially attractive scenarios using tidal current power supplemented with wind power, against a coal-fired plant with CCS, for BSR and No BSR RO Plants at Newhaven.

As can be seen from Figure 84 above, the most favourable option when using tidal current power supplemented by wind power at Newhaven, is just over 1.35x the estimated cost associated with using a coal-fired plant with CCS. The tidal current/ wind power based system is estimated to require 4276kW of tidal current power and 13720kW of wind power (17996kW in total) for a Pressure Exchanger BSR RO plant with just over 12000m^3/day capacity.

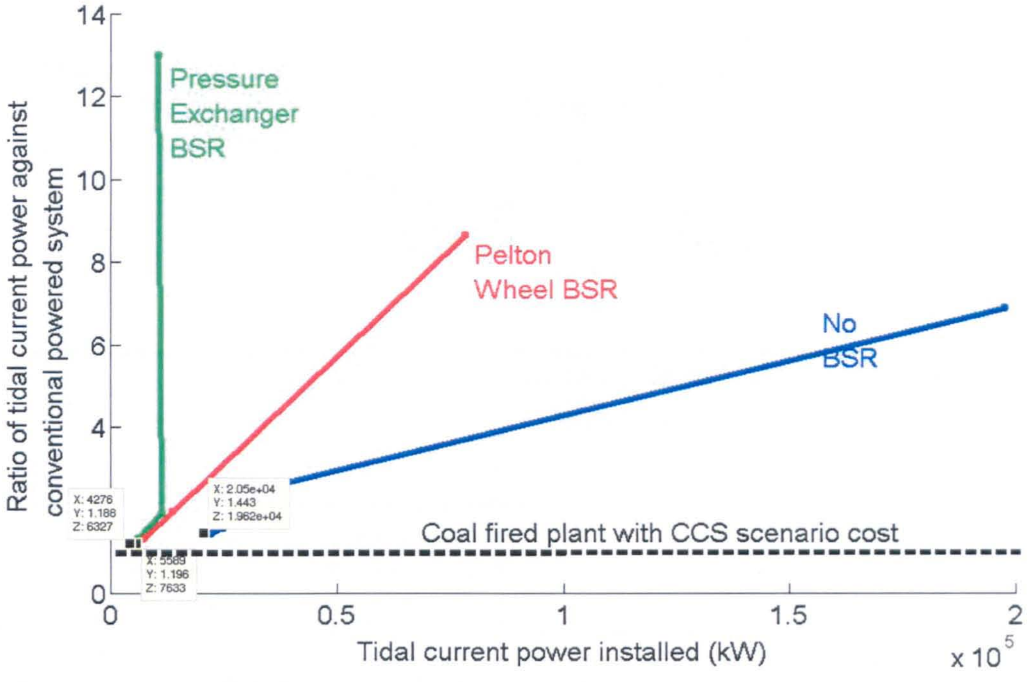

Figure 85: Cost ratio of most financially attractive scenarios using tidal current power supplemented with wave power, against coal-fired plant with CCS, for BSR and No BSR RO Plants at Newhaven.

As can be seen from Figure 85 above, the most favourable option when using tidal current power supplemented by wave power at Newhaven is just under 1.19x the estimated cost associated with using a coal-fired plant with CCS. The tidal current/ wave power based system is estimated to require 4276kW of tidal current power and 6237kW of wave power (10513kW in total) to be installed with a Pressure Exchanger BSR RO plant, with just under 9000m^3/day capacity.

6.4.4 Stage 4 – Addition of Hydrogen Fuel

6.4.4.1 Stage 1 and 2 scenarios with Hydrogen fuel at Massawa

As can be seen from Figure 86 below, the most favourable option when using solar power with hydrogen fuel at Massawa, is just over 1.4x the estimated cost associated with using a diesel generator. The Pressure Exchanger BSR RO plant solar-based system is estimated to require 17390kW of solar power to be installed for an RO plant with 10442m^3/day capacity.

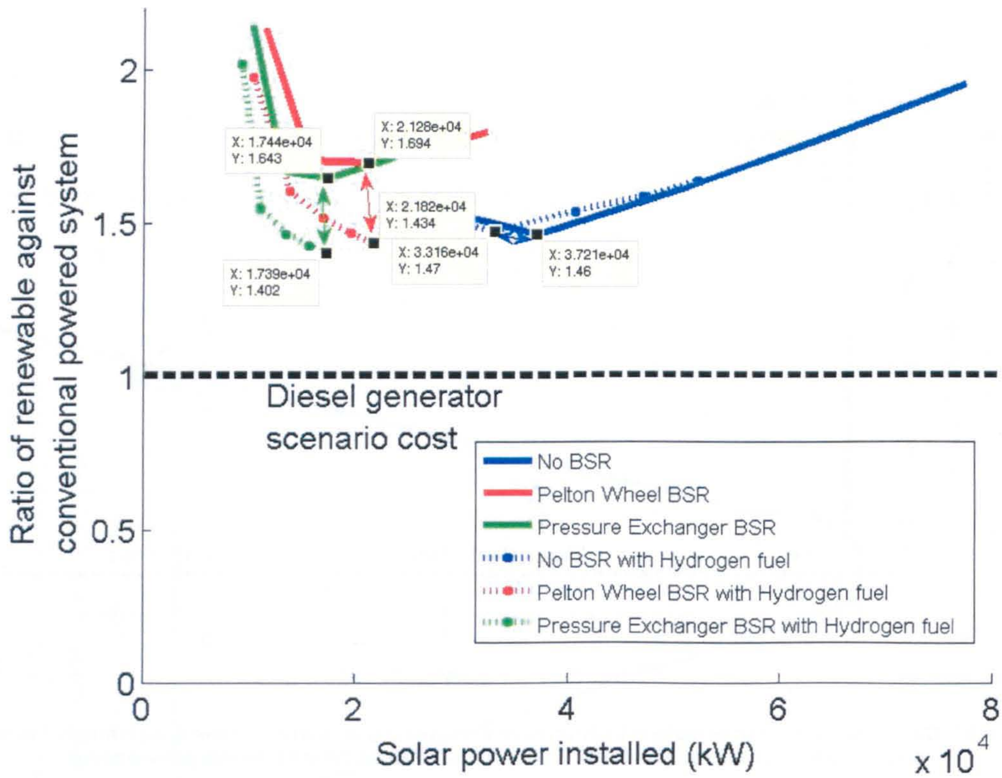

Figure 86: Cost ratio of scenarios using solar power supplemented with hydrogen storage use, against diesel generator powered system, for BSR and No BSR RO Plants

As can be seen from the red and green arrows in Figure 86 above, the addition of hydrogen storage improved the financial attractiveness of the BSR RO plant scenarios, reducing the ratio of financial viability from over 60% from financial viability to within 45%. The financial viability of the No BSR scenarios was generally improved except for the most financially attractive scenario (as shown by the blue arrow), which became less financially viable in comparison to the equivalent scenario without hydrogen fuel.

The reason for this is explained by a ratio termed the Coefficient of Financial Performance (CoFP). The CoFP is derived as follows:

$$CoFP = Cost_{sav}/Cost_{hf}$$

where:

$Cost_{sav}$ = The reduction in cost of scaled-up RO plant and power installed due to use of hydrogen fuel. (£)

$Cost_{hf}$ = The cost of hydrogen conversion and storage equipment, and fuel cells. (£)

This produced a unit that provides an indication of the cost effectiveness of using hydrogen fuel.

A CoFP greater than 1 indicates that it is not cost effective to employ hydrogen fuel for a scenario. The CoFPs for the No BSR scenarios shown in Figure 86 above are illustrated in Figure 87 below.

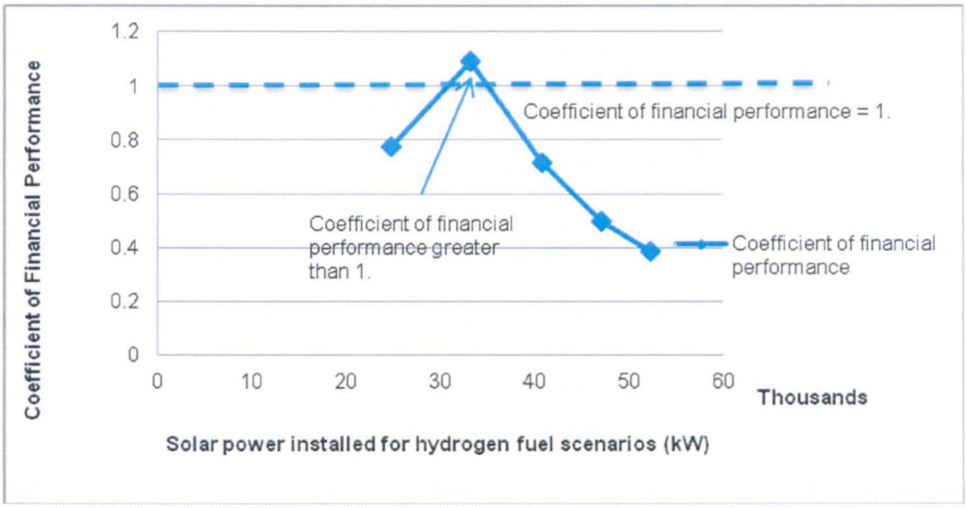

Figure 87: CoFPs of scenarios using solar power for the No BSR RO Plant at Massawa

As can be seen from Figure 87 above, the second scenario, (which is shown in Figure 86, by the blue arrow, to be less financially attractive when hydrogen fuel is used), had a CoFP of more than one. This means that the cost reduction, due to a smaller RO plant and less solar power being installed, is outweighed by the cost of the hydrogen fuel infrastructure required to achieve that cost reduction.

6.4.4.2 Stage 1 and 2 scenarios with Hydrogen fuel at Newhaven

Figure 88 below presents the comparison of estimated costs for tidal current with hydrogen fuel, for BSR and No BSR RO plants at Newhaven, against a coal-fired plant with CCS. The tidal current scenarios without hydrogen fuel use are also included for comparison.

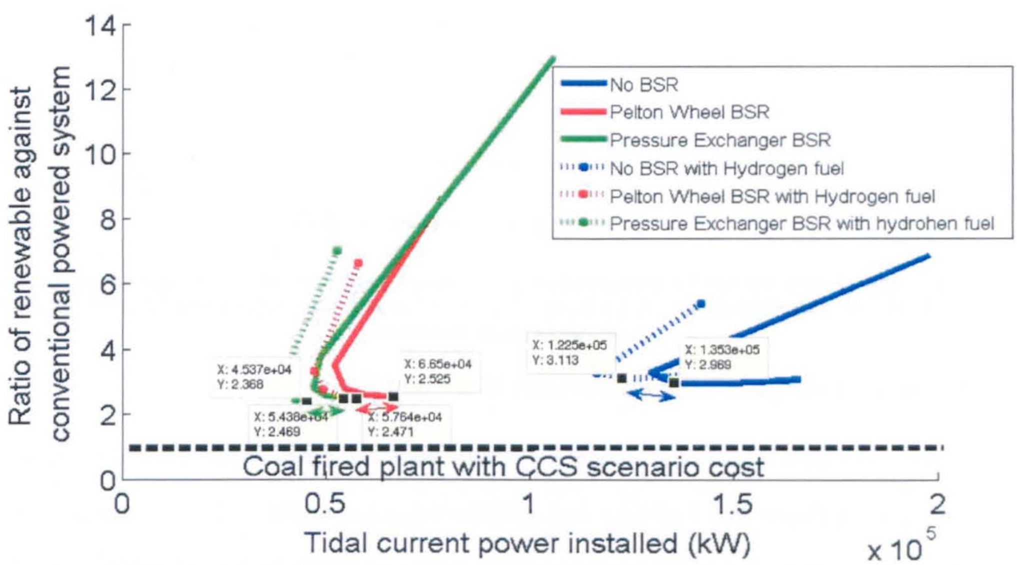

Figure 88: Cost ratio of scenarios using tidal current power with hydrogen storage use, against a coal-fired plant with CCS, for BSR and No BSR RO Plants, at Newhaven.

As can be seen from Figure 88 above, the cheapest option when using tidal current power with hydrogen at Newhaven, is just under 2.37x the estimated cost associated with using a coal-fired plant with CCS. The tidal current based system is estimated to require 45370kW of tidal current power, for a Pressure Exchanger BSR RO plant with 19025m^3/day capacity.

6.4.4.3 Massawa – solar plus wave power with Hydrogen fuel.

As with Stage 3, for the purpose of clarity only the most financially-attractive scenarios are shown for Stage 4 results using wind and wave power.

It can be seen from Figure 89 below, that the most favourable option when using solar power supplemented by wave power and hydrogen at Massawa is just over 1.21x the estimated cost associated with using a diesel generator. The solar/ wave-based system is estimated to require 2665kW of solar power and 8144kW of wave power (10809kW in total) for a Pressure Exchanger BSR RO plant with 8000m^3/day capacity.

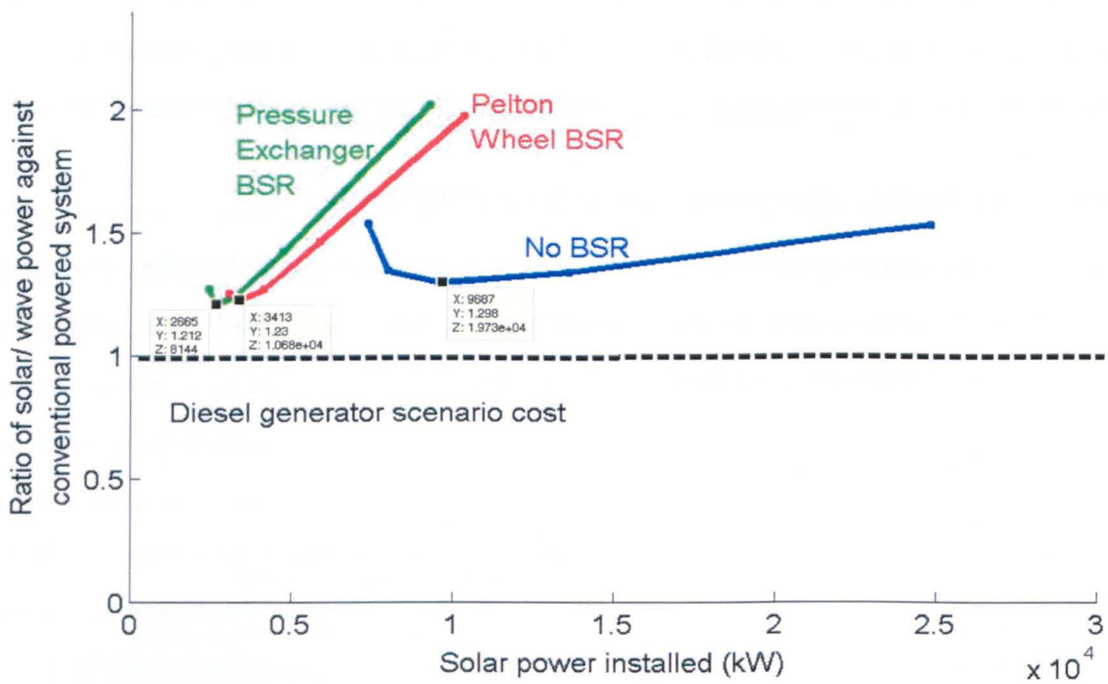

Figure 89: Cost ratio of most financially attractive scenarios using solar powered system against diesel powered system for BSR and No BSR RO Plants, using varying amounts of solar power supplemented by wave power plus hydrogen fuel, at Massawa.

6.4.4.4 Massawa – solar plus wind power with Hydrogen fuel.

As can be seen from Figure 90 below, the most financially-attractive option when using solar power supplemented by wave power with hydrogen fuel at Massawa is just under 1.19x the estimated cost associated with using diesel. The solar/ wave-based system is estimated to require 3560kW of solar power and 9775kW of wind power (13335kW in total) for a Pelton Wheel BSR RO plant with 8660m^3/day capacity.

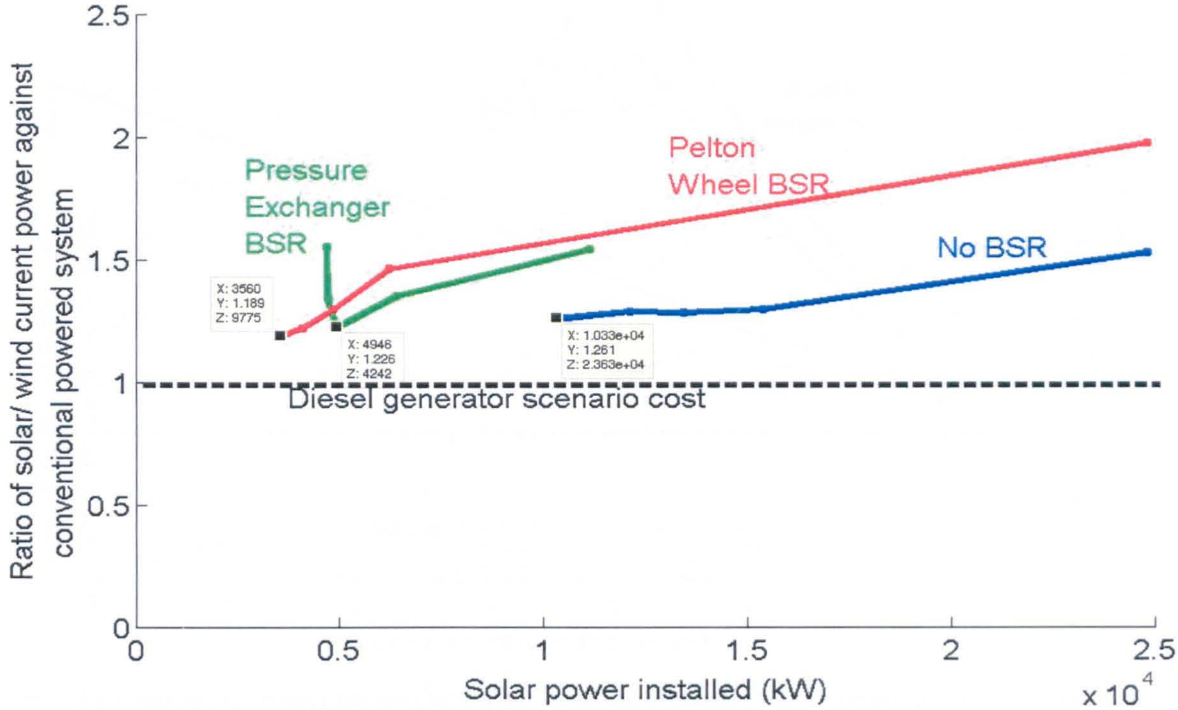

Figure 90: Cost ratio of most financially attractive scenarios using solar powered system against diesel powered system, for BSR and No BSR RO Plants using varying amounts of solar power supplemented by wind power plus hydrogen fuel, at Massawa.

6.4.4.5 Newhaven – Tidal current plus wave power with Hydrogen fuel

As can be seen from Figure 91 below, the most financially attractive option when using tidal current power supplemented by wave power with hydrogen fuel at Newhaven, is just over 1.2x the estimated cost associated with using a coal fired plant with CCS. The tidal current/ wave-based system is estimated to require 4283kW of tidal current power and 4753kW of wave power (9036kW in total) for a Pressure Exchanger BSR RO plant with 8980m^3/day capacity.

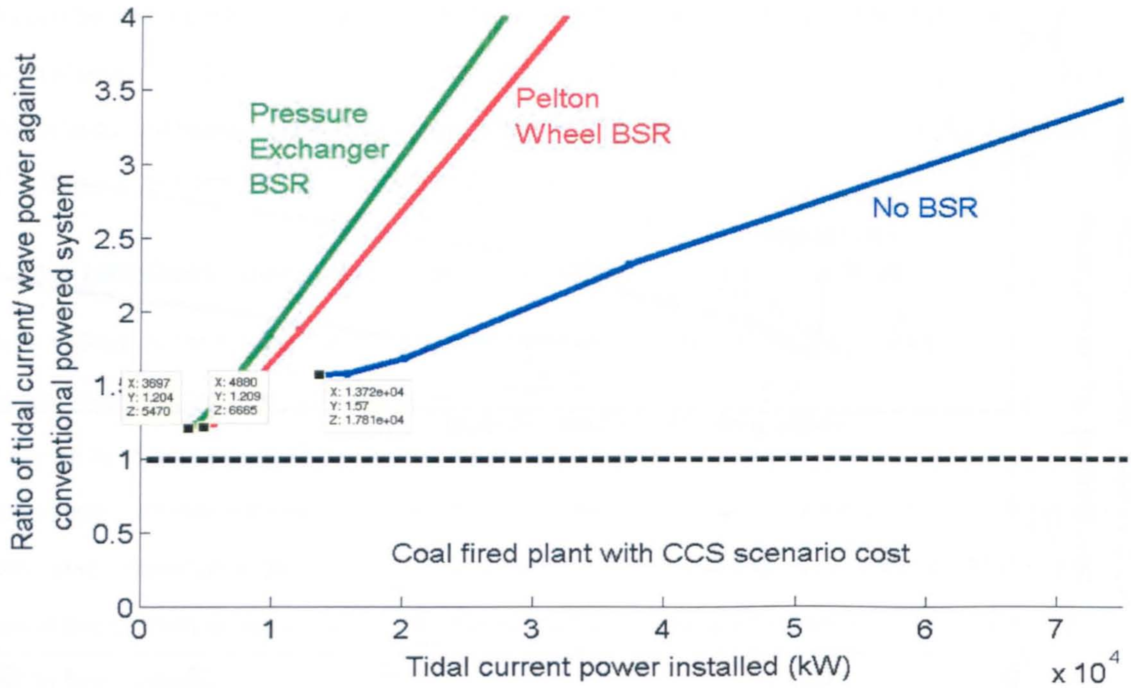

Figure 91: Cost ratio of most financially attractive scenarios using tidal powered system against coal-fired plant with CCS, for BSR and No BSR RO Plants, using varying amounts of solar power supplemented by wave power plus hydrogen fuel, at Newhaven

6.4.4.6 Newhaven – Tidal current plus wind power with Hydrogen fuel

As can be seen from Figure 92 below, there are no financially viable options when using tidal current power supplemented by wind power and hydrogen fuel at Newhaven. The most financially-attractive option when using tidal current power supplemented by wind power with hydrogen fuel to operate an RO plants at Newhaven is just under 1.2x the estimated cost associated with using a coal fired plant with CCS. This tidal current/ wind-based system is estimated to require 3475KW of tidal current power and 8326kW of wind power (11801kW in total), for a Pressure Exchanger BSR RO plant with 8520m^3/day capacity.

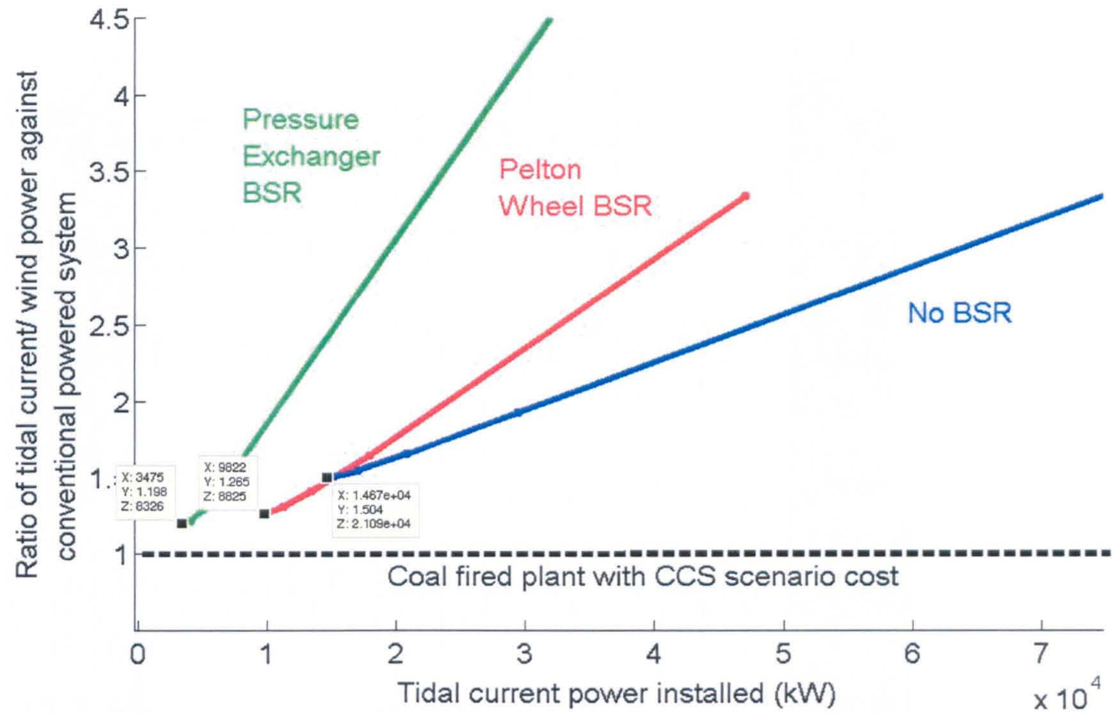

Figure 92: Cost ratio of most financially attractive scenarios using tidal powered system against coal fired plant with CCS, for BSR and No BSR RO Plants, using varying amounts of solar power supplemented by wind power plus hydrogen fuel, at Newhaven.

6.5 The consolidated results

Table 51 and 52 below show the consolidated results in terms of the most financially-attractive scenarios identified for Massawa and Newhaven, respectively for each stage. It is presented in order of modelling stages, with:

- The primary and secondary power installed, with the percentages of the full scenario power for primary and secondary power
- The scaled-up RO plant capacity for each of the most attractive scenarios.

The right hand column shows the multiples of renewable power installed in relation to the equivalent conventionally-powered scenario

Table 51: Technically-competent and most financially-attractive scenarios at Massawa.

Stage	Type of RO plant	Solar Power (MW) Percentage of power installed (%)	Secondary Power	Secondary Power (MW) Percentage of power installed (%)	Hydrogen fuel used?	Total installed power (MW)	RO plant capacity ($x10^3m^3$/day)	Ratio of renewable scenario cost against conventional energy cost	Ratio of Renewable power installed to conventional energy required
1	No BSR	37.2 (100)	None	0 (0)	No	37.2	18.6	1.46	12.4
2	Pelton Wheel	21.8 (100)	None	0 (0)	No	21.8	17.0	1.694	17.0
	Pressure Exchanger	17.4 (100)	None	0 (0)	No	17.4	17.5	1.643	17.4
3	No BSR	17.37 (63.6)	wind	9.93 (36.4)	No	27.3	17.4	1.227	9.1
	Pelton Wheel	3.69 (20.1)	wind	14.68 (79.9)	No	18.37	12.8	1.353	14.7
	Pressure Exchanger	2.98 (19.4)	wind	12.41 (80.6)	No	15.39	11.3	1.423	15.4
	No BSR	15.82 (41.7)	wave	22.14 (58.3)	No	37.96	10.9	1.289	12.7
	Pelton Wheel	4 (24.2)	wave	12.53 (75.8)	No	16.53	9.6	1.286	13.2
	Pressure Exchanger	2.98 (20.0)	wave	12.15 (80.0)	No	15.13	11.3	1.273	15.1
4	No BSR	33.16 (100)	None	0 (0)	Yes	33.16	16.6	1.47	11.1
	Pelton Wheel	21.82 (100)	None	0 (0)	Yes	21.82	10.5	1.434	17.5
	Pressure Exchanger	17.39 (100)	None	0 (0)	Yes	17.39	10.4	1.402	17.4
	No BSR	9.69 (32.9)	wave	19.73 (67.1)	Yes	29.42	9.7	1.298	9.8
	Pelton Wheel	3.41 (24.2)	wave	10.68 (75.8)	Yes	14.09	8.2	1.23	11.3
	Pressure Exchanger	2.67 (24.7)	wave	8.14 (75.3)	Yes	10.81	8.0	1.212	10.8
	No BSR	10.33 (30.4)	wind	23.63 (69.6)	Yes	33.96	13.5	1.261	11.3
	Pelton Wheel	**3.56 (26.7)**	**wind**	**9.775 (73.3)**	**Yes**	**13.34**	**8.7**	**1.189**	**10.7**
	Pressure Exchanger	4.945 (53.8)	wind	4.242 (46.2)	Yes	9.187	11.2	1.226	9.2

Table 52: Technically-competent and most financially-attractive scenarios at Newhaven.

Stage	Type of RO plant	Tidal Current Power (MW) Percentage of power installed (%)	Secondary Power	Secondary Power (MW) Percentage of power installed (%)	Hydrogen fuel	Total installed power (MW)	RO plant capacity ($x10^3 m^3/day$)	Ratio of renewable scenario cost against conventional energy cost	Ratio of Renewable power installed to conventional energy required.
1	No BSR	135.3 (100)	None	0 (0)	No	135.3	28.4	2.969	30.6
2	Pelton Wheel	66.5 (100)	None	0 (0)	No	66.5	20.9	2.525	36.5
	Pressure Exchanger	54.38 (100)	None	0 (0)	No	54.38	22.8	2.469	38.0
3	No BSR	20.5 (41.0)	wind	29.48 (59.0)	No	49.98	12.9	1.527	11.3
	Pelton Wheel	5.59 (28.4)	wind	14.12 (71.6)	No	19.71	12.4	1.38	10.8
	Pressure Exchanger	4.28 (23.8)	wind	13.72 (76.2)	No	18	12.0	1.358	12.6
	No BSR	20.50 (51.1)	wave	19.62 (48.9)	No	40.12	9.5	1.443	9.1
	Pelton Wheel	5.59 (42.3)	wave	7.63 (57.7)	No	13.22	8.8	1.196	7.3
	Pressure Exchanger	4.28 (40.3)	wave	6.33 (59.7)	No	10.61	9.0	1.188	7.4
4	No BSR	122.5 (100)	None	0 (0)	Yes	122.5	25.7	3.118	27.7
	Pelton Wheel	54.38 (100)	None	0 (0)	Yes	54.38	18.1	2.474	29.9
	Pressure Exchanger	45.37 (100)	None	0 (0)	Yes	45.37	19.0	2.371	31.7
	No BSR	13.72 (43.5)	wave	17.81 (56.5)	Yes	31.53	8.6	1.57	7.1
	Pelton Wheel	4.88 (42.3)	wave	6.67 (57.7)	Yes	11.55	7.7	1.209	6.3
	Pressure Exchanger	3.7 (40.3)	wave	5.47 (59.7)	Yes	9.17	7.8	1.204	6.4
	No BSR	14.67 (41.0)	wind	21.09 (59.0)	Yes	35.76	9.2	1.504	8.1
	Pelton Wheel	9.82 (52.7)	wind	8.825 (47.3)	Yes	18.645	7.7	1.265	10.2
	Pressure Exchanger	3.475 (29.4)	wind	8.326 (70.6)	Yes	11.801	7.3	1.198	8.3

6.5.1 Discussion of the results

When scaled-up, all the modelled renewable-powered scenarios were able to achieve the water production required to meet the local users' demands. This though required a significant amount of installed power, in comparison to the conventionally-powered scenarios. At Newhaven, this meant that, in the worst case, almost 40 times the conventionally-powered scenario power capacity needed to be installed, to produce the required amount of water for certain scenarios. This said, the lowest installed power ratio was also at Newhaven, with the Pelton Wheel with wave and hydrogen fuel scenario, which only required 6.3 times the conventional scenario's power capacity. The installed power ratios were more consistent at Massawa, falling in the range of 9 – 18 times the conventional scenario's power capacity. It is also apparent that there is a wide range of cost differences for the scenarios at Newhaven, ranging between 1.2 and 3 times the cost of the coal-fired plant with CCS scenarios, but once again the Massawa scenario show more consistency falling in the lower range of 1.2 – 1.7 times the cost of the diesel powered scenarios. So it can be seen that the correct combination of RO plant size and quantity of installed power, is vitally important so as to achieve the most financially-attractive result.

6.5.1.1 Stage 1 and 2

At Massawa, the most financially-attractive solar-powered options required between 12 and 17 times the installed power to match the diesel power required. At Newhaven, with the tidal current power devices, this ratio more than doubled to between 30 and 38 times the power that would be required with a coal-fired plant with CCS.

The tidal current speeds at Newhaven are relatively low at 1.5m/s maximum, and in light of the inefficiency at low tidal speeds the SeaGen was effectively selected as an academic exercise as it was the most developed device available. It is considered that other, less developed devices, that are able to generate power at lower tidal current speeds are more realistic options and worthy of further consideration for locations such as Newhaven.

There are also areas on the south coast of England, such as the waters south of the Isle of Wight, with estimated tidal current speeds of 2.5m/s [SEEDA, 2007], which would make a significant difference to the volume of installed tidal current power required, and the financial attractiveness of all the tidal current scenarios.

It is noteworthy that:

- There is a significant shortfall to make up with the tidal current scenarios being 2.5 – 3 times as expensive as the coal-fired plant with CCS

- That the use of less developed devices with better low speed generation capabilities would improve performance at Newhaven, but are less technically developed and costs are less well understood, and
- Remote power generation would require the power to be transmitted to its point of use at Newhaven, and this may incur losses.

There are a variety of options to enhance the viability of the scenarios at Massawa,by making greater use of the sun, by tracking on one or two axis, and use of Concentrated Solar Power [Philibert, 2010]. The costs due to installed solar power as a percentage of the full scenario costs at Massawa are shown below in Figure 93.

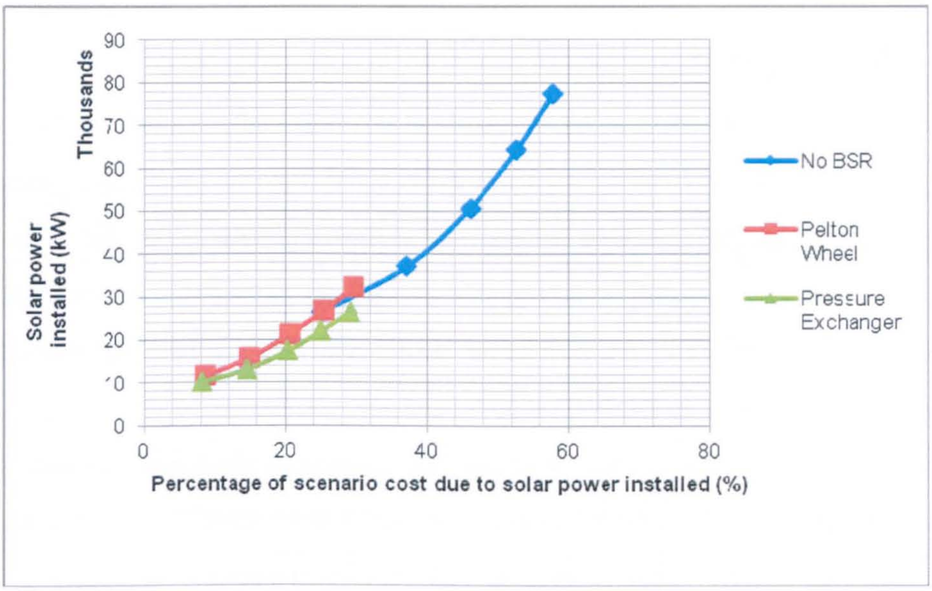

Figure 93: Percentage of scenario cost due to solar power installed.

As can be seen from Figure 93 above, the BSR RO plants (Pelton Wheel and Pressure Exchanger) use relatively small amounts of power. Hence, the proportion of the overall scenario costs due to installed solar power is relatively low (between 8 and 30%). As such it is unlikely that the increase in efficiency due to CSP alone could make these scenarios financially viable, as the shortfall is around 70% and 65%, for the Pelton Wheel and Pressure Exchanger, respectively.

The No BSR scenarios though, use more solar power, (between 25% and 57%), and have a shortfall of only 46% to financial viability. Therefore, it is expected that the use of more sophisticated solar power conversion would have the greatest impact on the No BSR scenarios to improve their prospects for financial viability.

CSP requires a cooling water cycle to achieve the best efficiency. If the CSP cooling water cycle could be used to pre-heat the feedwater for the RO plant, it would increase the output of permeate for the same power input, and improve the prospects for financial viability.

There are, however,concerns about the water consumed by the steam cycle, of the closed-loop system employed by CSP plants,which could be as much as 3.5m^3/MWh [Glennon and Reeves, 2010]. This water consumption rate would mean that 3.8%, 2% and 1.7% of the annual water production would be consumend within the steam cycle for the most financially-attractive No BSR, Pelton Wheel BSR and Pressure Exchanger BSR RO plants modelled, respectively. So, the efficiency of the closed-loop CSP plant versus the reduction in efficiency associated with the air-cooled CSP, (which has significantly reduced water consumption), will need to be considered in light of the potential steam cycle water demand if the CSP option is to be progressed further.

6.5.1.2 Stage 3 – Addition of wind and wave power

6.5.1.2.1 Addition of wind

At Massawa, the No BSR option with wind requires the smallest installed power ratio of all the Massawa scenarios (at 8 times the diesel scenario), but the BSR RO plants using the same type of power source require significantly greater ratios (around 15 times the conventional scenarios installed capacity). Interestingly, the third most financially attractive option at Massawa (highlighted in italics in Table 51 above) uses around 64% solar and 36% wind power, but the other less financially attractive BSR RO plant options are made up of around 80% wind power and 20% solar power.

Massawa has almost the worst wind profile in Eritrea [Habtetsion et al, 2002], and it is reasonable to assume that if the wind turbines were sited at a location such as Dekemhara, Gizgiza, Assab or Gahro with significantly increased and relatively predictable wind speeds, the power needed could be achieved with significantly less installed wind power capacity, which would further improve the prospects for financial viability.

The same principle applies at Newhaven, with its wind-based scenarios being made up of between 50% and 60% installed wind power. As can be seen from WEBvision – Renewables (Wind) [ABPMER, 2011a], if the turbines were sited offshore they would benefit from significantly increased wind speeds. The further offshore they are sited, the greater the improvement in wind speed and potential to make up the 35 – 50% shortfall, and become financially viable. It is though noteworthy, that locating turbines offshore does increase the complexity of maintenance, and operation of the turbines, which could adversely impact the viability of the scenario.

6.5.1.2.2 Addition of wave

With regard to wave power, the scenarios are around 28% and 19% – 44% short of financial viability at Massawa and Newhaven, respectively. Newhaven has wave plus tidal as its most financially-attractive scenario modelled as highlighted in bold in Table 52 above. Although there is little information available regarding the wave potential at Massawa, the UK has a significant wave resource [ABPMER, 2011b], with examples in the South West of England having more than double the wave power density found at Newhaven.

It is reasonable to assume that if wave power and tidal current devices were sited at an energy farm in the south west of England (or even south of the Isle of Wight), the minimal shortfall to financial viability could be made up, if the power could be transmitted to Newhaven efficiently enough.

6.5.1.3 Stage 4 - Addition of hydrogen fuel

Table 53 provides details of the impact of the addition of hydrogen fuel in terms of the reduction in plant size and cost using the comparison of the most viable scenarios at each stage.

Table 53: Impact of the addition of hydrogen Fuel at Massawa and Newhaven

Type of RO plant	Massawa			Newhaven		
	Power Source	Reduction in plant size (%)	Impact on cost (+/- %)	Power Source	Reduction in plant size (%)	Impact on cost (+/- %)
No BSR	Solar	10.75	-0.68	Tidal Current	9.51	-5.02
Pelton Wheel	Solar	38.24	15.35	Tidal Current	13.40	2.02
Pressure Exchanger	Solar	40.57	14.67	Tidal Current	16.67	3.97
No BSR	Solar + Wind	22.41	-2.77	Tidal Current + Wind	33.33	-2.82
Pelton Wheel	Solar + Wind	32.03	12.12	Tidal Current + Wind	37.90	12.39
Pressure Exchanger	Solar + Wind	0.88	13.84	Tidal Current + Wind	35.00	11.34
No BSR	Solar + Wave	11.01	-0.70	Tidal Current + Wave	3.16	-4.23
Pelton Wheel	Solar + Wave	14.58	4.35	Tidal Current + Wave	12.50	-5.77
Pressure Exchanger	Solar + Wave	29.20	4.79	Tidal Current + Wave	18.89	-0.84

As can be seen from Table 53 above, although the addition of hydrogen fuel allows less power capacity to be installed, its impact on financial viability varies for the different RO plant types at Massawa and Newhaven.

The No BSR RO plant scenario's financial viability ratios increased, (got worse as indicated by the –ve Impact on cost in Table 53 above), with the addition of hydrogen fuel, whereas the BSR scenario financial viability generally improved slightly when hydrogen fuel was employed.

At Massawa, the No BSR scenario's financial attractiveness was slightly reduced, by 3% maximum, in comparison to the non-hydrogen scenario, and the BSR RO plant type's financial attractiveness increased by around 15%, 13% and 4.5% for the Solar, Solar + Wind and Solar + Wave scenarios, respectively.

At Newhaven the use of hydrogen fuel gave a slight improvement to financial attractiveness to a minority of the scenarios analysed only, and at best only achieved a financial benefit of around 12% against the scenario without hydrogen fuel. Although the reductions in installed power due to hydrogen storage at both sites for the most financially-attractive options were in the order of 40% maximum, with a reuse efficiency of only 22%, the costs were only reduced by 15% at best. This would indicate that the costs associated with the infrastructure for hydrogen production, storage and fuel cells for re-use, outweighed the benefit of reduced installed power and RO plant size. Taking the case of the scenario with the best CoP identified at section 6.2.1.3, (Tidal current powered Pressure Exchanger BSR RO Plant), the use of hydrogen fuel resulted in a cost reduction of over 45% over the non-hydrogen fuelled example, and the hydrogen infrastructure made up only 3.6% of the cost of the scenario.

In this case though, the original non-hydrogen fuelled scenario had the worst water production capability of all, at just over 3%, and had to be scaled-up by around 30 times to meet the needs of the local users. The reduction of scale-up (to just under 16 times) due to the use of hydrogen fuel, meant that the scenario would cost around 7 times that of the conventionally powered equivalent.

Overall, it is evident that the advantage that desalination offers when water storage is available, the ability to batch produce and store energy as water produced rather than operate continuously, varies according to RO plant type and input power source. In simple terms, it was only cheaper to oversize the RO plant and its power supply for the No BSR RO plants at Massawa, but at Newhaven it was cheaper for the No BSR scenarios as well as the tidal current with wave powered scenarios. The scenarios employed hydrogen at 22% round trip efficiency, but if a technology such a Redox cells could be employed with its reuse efficiency of around 80% [Thwaites, 2007], it is possible that it could make up the 45% shortfall of the Massawa BSR RO plants (see Table 51), and become financially viable when compared to conventional equivalents, if it is not too expensive to implement and operate such a system. It is also noteworthy, that the energy re-use was applied to maintain the maximum flowrate. There is the option to oversize the RO plant, such that the stored energy can be applied to maintain the RO plant at it optimum efficiency, and meet the needs of the users. The optimum flow is typically 70 - 87% of that at full flow[88], and could improve the financial attractiveness of energy storage scenarios, if the efficiency benefits are not outweighed by the cost of the RO Plant enlargement.

This methodology could also be extended to oversize the installed power infrastructure to provide surplus power to meet the energy needs of the local community, as shown below in Figure 94.

[88] There was an outlier at 9ºC for the Pelton Wheel BSR RO plant where the optimum specific power consumption was 96.8% of that required at full flow. This was disregarded.

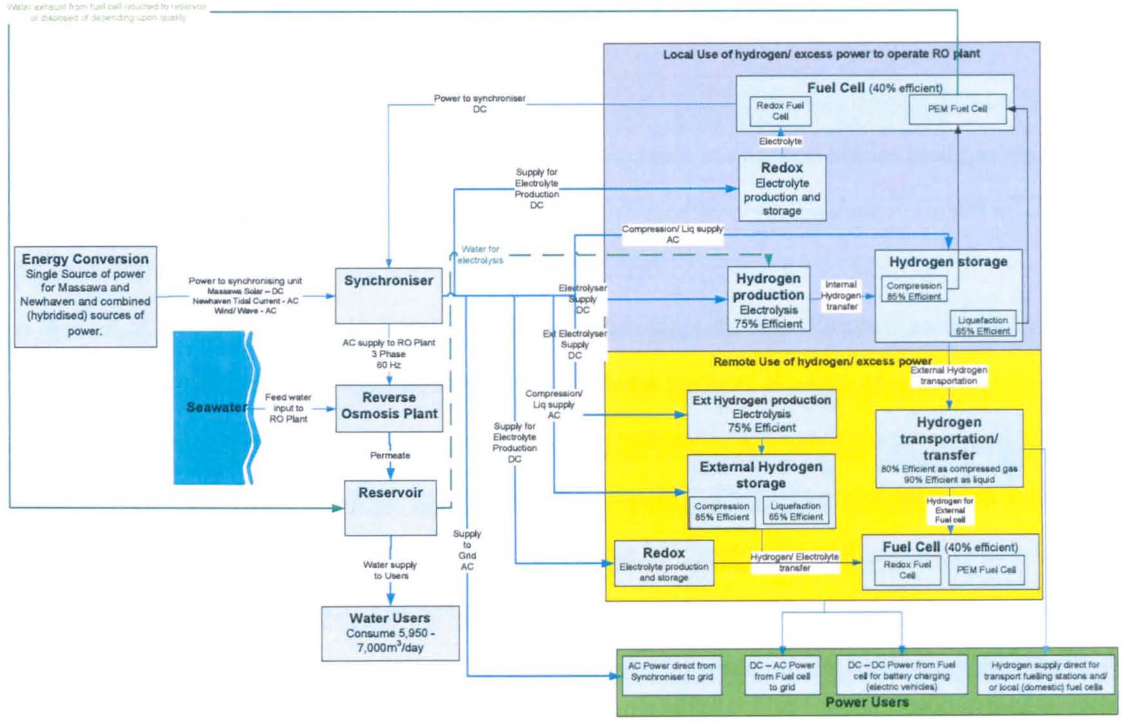

Figure 94: Re-use of wasted energy to RO plant and external users

Figure 94 above shows a model that could be adopted for an oversized power plant, producing excess electricity for storage and re-use when the needs of the RO plant are serviced, and includes the use of Redox electrolyte and fuel cells. The sale of the surplus hydrogen/ electrical power could then be used to offset the additional cost associated with the enlarged power plant.

6.5.1.3.1 Addition of wind/ wave

At Massawa, for both wave and wind, the No BSR RO plant scenario's financial attractiveness worsened with the addition of hydrogen fuel, whereas the BSR scenario's financial attractiveness improved when hydrogen fuel was employed. The Pelton wheel BSR with wind, (which was the most financially attractive scenario as highlighted in bold in Table 52 above), improved to the extent that it was less than 19% short of financial viability.

Of the two options (wind or wave) for Massawa to pursue further, it was considered that the greatest understood potential to improve was based on wind, through the installation of wind turbines in areas of Eritrea with better winds, to further improve the prospects for financial viability.

At Newhaven, the situation was reversed, with all wave scenarios becoming more expensive (less financially attractive) with the addition of hydrogen fuel, but wind-based scenarios reduced in cost for all the RO plants modelled. All the options modelled were within 60% of financial viability, and the Pressure Exchanger with wind and hydrogen fuel was only 20% short of financial viability. If the examples of improvements stated above were applied, it was considered that the prospects for financial viability would be significantly improved for all varieties of Stage 4 scenarios.

Overall, it is concluded that the benefit associated with the reduction of installed RO and renewable power assets required for the scenario to meet the required water production often results in a cost reduction over the equivalent scenario without hydrogen fuel, but not always. The limited round trip efficiency and the high cost of the hydrogen associated assets means that the use of hydrogen does not necessarily guarantee a more financially viable scenario. The benefit that desalination has, to be able to effectively store energy as water, is inherent whether or not hydrogen storage is employed. So the benefit of energy storage in these scenarios was simply to reduce the energy wasted due to providing power above/ below the range that the RO plant could use. As such the benefit of being able to 'load follow' that energy storage has the potential to provide, was not available in these desalination scenarios and the impact of the limited importance of 'dispatchability' has shown in the results that the energy storage scenarios modelled did not always produce the most financially viable option.

6.5.2 Complexity of the scenario

The complexity of the equipment is a potential aspect of the viability of any scenario, and Table 54 and Table 55 below present the scenarios with the cost ratio against the equivalent conventionally powered scenarios at Massawa and Newhaven, respectively.

The scenarios were categorised using a traffic light system, for their complexity in operation and maintenance with:

Green being the easiest to operate and maintain

Amber being more difficult to operate and maintain, and

Red being the most difficult to operate and maintain.

The scenarios that are the most financially-attractive in each category, are highlighted in 'bold'.

Table 54: Massawa Ratios, with complexity of operation and maintenance

	Solar Power	Solar+ Wind	Solar+ Wave	Solar+ H_2	Solar+ Wind+ H_2	Solar+ Wave +H_2
No BSR	1.46	**1.23**	1.3	1.47	1.26	1.30
Pelton Wheel BSR	1.69	1.35	**1.28**	1.43	**1.19**	1.23
Pressure Exchanger BSR	1.64	1.42	1.27	1.40	1.23	1.21

Table 55: Newhaven Ratios, with complexity of operation and maintenance

	Tidal Current (TC) Power	TC+ Wind	TC+ Wave	TC $+H_2$	TC +Wind $+H_2$	TC+ Wave $+H_2$
No BSR	2.97	**1.53**	1.44	3.11	1.50	1.57
Pelton Wheel BSR	2.53	1.38	**1.20**	2.47	1.27	1.21
Pressure Exchanger BSR	2.47	1.36	**1.19**	2.37	1.20	1.20

As can be seen from the Tables above, at Newhaven the more financially-attractive scenarios are quite complex, with the renewable powered Pelton Wheel and Pressure Exchanger BSR RO plants achieving the most financially-attractive results. They were more than 30% closer to financially viable than the easiest option to implement (no BSR with tidal current and wind power). This is also true at Massawa, where the most financially attractive options all use hybridised power and hydrogen fuel. Interestingly, the option at Massawa that is third most attractive, (four percent short of the most favourable with a cost ratio of 1.23), uses one of the least complex combinations modelled, solar and wind power applied to a No BSR RO plant.

Of the simplest options (highlighted in 'green'):

Primary power with wind is the most attractive at both sites. Interestingly, the avenue for the two sites to employ to improve their financial viability differs in terms of the difficulty of implementation. At both sites, there are surrounding areas with well-understood wind resources, but the difference is that in Eritrea they are on-shore, and in Newhaven they are mainly offshore.

In the case of onshore windfarms, they are well established, whereas offshore wind presents a variety of engineering, operational and maintenance difficulties. Thus, it is considered that the Massawa option to use solar in combination with onshore wind, remote from the point of use, is the most practical and financially-attractive option to pursue.

Of the more difficult options (highlighted in 'amber'):

At both Massawa and Newhaven, the option closest to financial viability is the use of primary power supplemented by wave power with the No BSR and Pelton Wheel RO plants at Massawa and Newhaven, respectively. The most logical option to pursue at Massawa to improve the prospects of this scenario is to make more efficient use of the solar power available due to the limited understanding of the wave resources available in the Red Sea.

At Newhaven, the most favourable avenue to pursue is to site the wave power devices at a location with better wave resources.

With regard to the Pelton Wheel RO plant itself, the use of brine stream recovery adds complexity, and as it is sized (and costed) for the fact that the Pelton Wheel will provide a portion of the process power required, in the event of failure, the RO plant will not be able to achieve its performance targets.

Of the most difficult options (highlighted in 'red'):

At Massawa, the most financially-attractive but difficult to operate option, is the No BSR RO plant with solar and wind power with hydrogen fuel.

At Newhaven, the most financially attractive option is the Pressure Exchanger BSR RO plant with tidal current and wave power.

The level of complexity of this scenario for Massawa (considering that it is modelled to operate continuously for 25 years) cannot be justified in comparison to the almost as financially-attractive, and significantly less complex, solar and wind scenario. It is though, considered that the most financially-attractive option at Newhaven, 'tidal current with wave power' (which is less complex than that at Massawa) is reasonable to pursue if the power sources are sited at locations with better wave and tidal current resources. This should not be a problem, with the established national grid in the UK.

6.6 Externalities of energy production and use

The objective of this research was to determine whether renewable energy sources are viable. The example used to investigate the viability was desalination, and in RO plants currently operated with conventional fuels, the hidden costs, (the externalities)[89], borne by society are not reflected.

This section will investigate the externalities of conventional energy use, and attempt to ascertain the credit (the 'X' Factor) to be applied to renewable energy sources to reflect any societal savings that their use (by displacing conventional fuels) may have.

The best available studies of externalities of power generation, are the European Union's (EU) 'ExternE Project' [ExternE, 2003], and its successor, 'New Energy Externalities Development for Sustainability (NEEDS)'. Drawing upon a huge body of research and analysis, ExternE has produced estimates of monetary costs of greenhouse, health, and other environmental impacts of power station emissions, based on full life-cycle assessments.

Figure 95 below shows the pollutants and the potential effects considered by ExternE.

[89] An external cost (also known as an externality) arises when the social or economic activities of one group have an impact on another group, which is not fully accounted or compensated for, by the first group, (e.g. a power station that generates emissions of SO_2, causing damage to building materials or human health, imposes an external cost). This is because the impact on the owners of the buildings or on those who suffer damage to their health is not taken into account by the generator of the electricity, when deciding on the design of the power station. In this example, the environmental costs are "external" because, although they are real costs to these members of society. The owner of the power station is not taking them into account when making decisions.

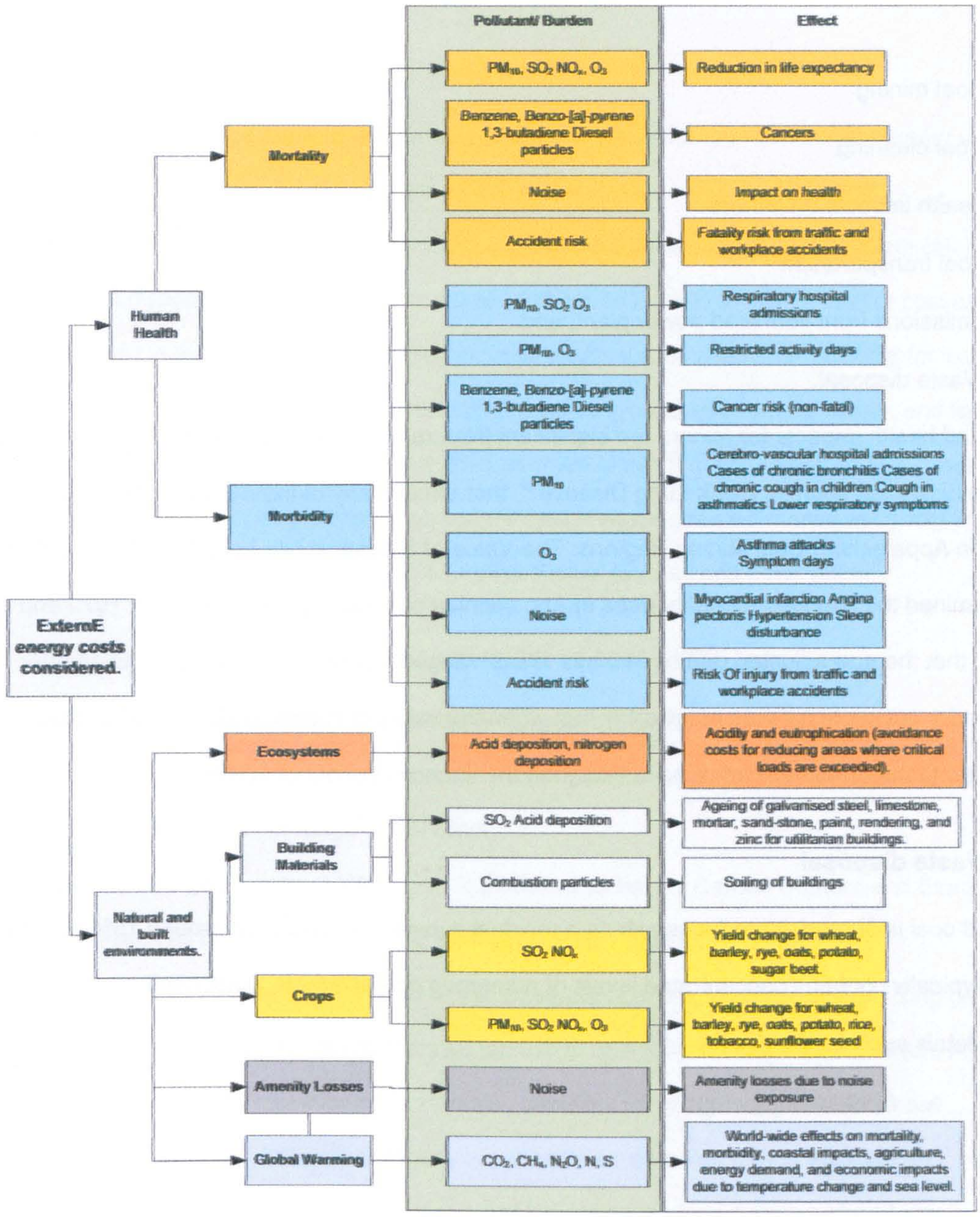

Figure 95: External energy costs considered by ExternE

The ExternE report clearly states that there is an unquantifiable level of error in their estimated costs when applied without taking the specifics of individual locations into account, so the estimates are only *indicative* of the costs due to the externalities associated with conventional electrical power generation.

6.6.1 Externalities associated with coal-fired plant with CCS technology, to be employed in Newhaven

'Cradle to Grave: the Environmental Impacts from Coal' [Clean Air Task Force, 2001], gives a concise overview of the impacts of coal throughout its life-cycle, when used to produce electricity.

It splits coal's lifecycle for electricity production into the following main stages where external impacts occur:

- Coal mining
- Coal cleaning
- Health impacts on miners
- Coal transportation
- Emissions from coal fired power plant, and
- Waste disposal.

The reported health impacts for miners are significant [Natural Capitalism Solutions, 2010], due largely to the severe diseases, such as Black Lung Disease[90], that affect many of them in their later years. 'Mortality in Appalachian Coal Mining Regions: The Value of Statistical Life Lost' [Hendrix and Ahern, 2009] examined the elevated mortality rates in Appalachian coal mining areas between 1979 and 2005, and found that the age-adjusted deaths in these areas, ranged from 3,975 to 10,923[91]. Even after adjustment for covariates, it was noteworthy that when the value of statistical life lost (VSL) was applied, the cost due to the premature fatalities outweighed the financial benefit of mining.

6.6.1.1 Waste disposal

When hard coal is burned, it produces ash as a residual substance making up around 15% by mass[92]. This ash typically contains concentrated levels of numerous contaminants, particularly:

- Metals such as:
  - Arsenic
  - Mercury
  - Lead
  - Chromium

---

[90] Coal miners are exposed to high levels of coal dust, which is damaging to the respiratory system. Some coal dust contains particles of quartz, the agent responsible for causing Coal Miner's Pneumoconiosis, or Black Lung. Miners who are stricken with Black Lung, experience shortness of breath, obstruction of airways, severe cough, and death. In the United States, 4.5% of coal miners (4,717 miners) were affected by Black Lung. Over 10,000 miners have died from Black Lung in the past ten years. About 0.2% of coal miners are diagnosed with Progressive Massive Fibrosis, an advanced form of Pneumoconiosis, where lesions are formed in the lungs causing shortness of breath and extreme pain. Between 1968 and 1992, more than 59,000 deaths – all male – were attributed to Black Lung.

[91] Of these deaths, approximately 2,300 were related to environmental factors, such as pollution of water and air made worse by mining. The extraction and production of coal emits pollutants such as mercury, sulphates (SO_4), nitrates (NO_3), carbon monoxide (CO), fine particulate matter ($PM_{2.5}$) and large particulate matter (PM_{10}).

[92] Approximately 80-85% of the ash exiting the furnace is extracted by mechanical and electrostatic precipitators. These are connected in series to remove the finer and lighter materials. The remaining 15-20% condenses on the boiler tubes, and subsequently falls to the bottom of the furnace, where it sinters to form furnace bottom ash.

- o Cadmium, and
- Radioactive elements[93] [Hvistendhal, 2007].

Within the UK, the ash is removed from the furnace to storage pits, prior to shipment. Its primary reuse is for the manufacture of concrete building blocks.

This, though, is not the case in many nations where the ash (now containing scrubbing chemicals) is stored locally and disposed of to landfill. There are several issues relating to this method of coal ash disposal (especially in the North America), which incur an external cost, due to the potential for increased incidence of cancer, and ash forming dust, which contaminates ground and surface waters, and food.

It is noteworthy that fly ash (comprising finely-divided particles of ash that are carried as flue gases after combustion of a fuel) has the potential to act as a significant revenue stream if managed correctly, as described within 'Ash utilisation from Coal-Based Power Plants' [Barnes and Sear, 2004].

6.6.1.1.1 ExternE assessment of externalities due to coal in UK

ExternE presents external costs for the use of coal & lignite in the UK of 4 – 7€ cent/kWh. For the purposes of this research, the external cost associated with electricity generation via coal at Newhaven was taken as the lower end of the range[94], 3.4p/kWh.

The conventional power plant used at Newhaven is modelled as having Carbon Capture and Storage (CCS), which is taken as being 90% efficient at removing carbon dioxide.

The final ExternE report provides a breakdown of the externalities of electricity production using coal in Germany, which is attributed with external costs for the use of coal & lignite of 3 – 6€ cent/kWh. For the purposes of this research, the breakdown of externalities presented for Germany was taken as reasonable to apply to the UK. Although Germany is generally accepted as having more efficient coal fired power stations[95], it is assumed that the plant in the UK will have at least the equivalent efficiency of a plant in Germany based on the 'Cleaner Coal Postnote' [POST, 2005].

---

[93] The Scientific American article states that:

> *'coal ash carries into the surrounding environment 100 times more radiation than a nuclear power plant producing the same amount of energy'.*

This quote though is put into perspective by the statement that:

> *'As a general clarification, ounce for ounce, coal ash released from a power plant delivers more radiation than nuclear waste shielded via water or dry cask storage.'*

and:

> *'The chances of experiencing adverse health effects from radiation are slim for both nuclear and coal-fired power plants—they're just somewhat higher for the coal ones. "You're talking about one chance in a billion for nuclear power plants,"* Christensen says. *"And it's one in 10 million, to one in a hundred million, for coal plants."*

[94] The coal-fired power station with CCS at Newhaven was given credit for being at the low end of the range of external costs, as it modelled as using integrated gasification combined cycle (IGCC), which is a new coal technology that ExternE identifies as having lower air pollution impacts.

[95] According to the 'Cleaner Coal Postnote,

> *'All UK coal-fired power stations use .... combustion processes with efficiencies of ~36–39%'* in comparison to the fact that *'Supercritical plants operating in Denmark and Germany reach efficiencies of 47%'.*

Of the external costs in Germany, those attributed to the avoidance of CO_2emissions[96], are 63% of the total external costs for producing electricity using coal. So, to take account of the coal-fired plant with CCS available to Newhaven, the external cost is reduced to take account of the CCS's efficiency (taken as 90%) at capturing CO_2. So, the cost due to externalities to power the RO plants at Newhaven was taken to be 1.47p/kWh[97].

6.6.2 Externalities associated with diesel generation to be employed in Massawa

ExternE presents external costs for the use of oil in the UK of 3 – 5€ cent/kWh. For the purposes of this research, the external cost associated with electricity generation via diesel to power the RO plants at Massawa was taken as the lower end of the range, at 2.5p/kWh.

6.6.2.1 Energy security

The International Center for Technology Assessment [CTA, 2005] presents a case for military and local storage costs in the US.

It makes the point that an indeterminate portion of the US, and other countries, defence budgets, are concerned with protecting oil supplies by maintaining regional stability in the countries that produce oil, including military support to maintain the stability of regimes, and military intervention to remove them. The estimated external costs associated with US military expenditure to protect the world's petroleum supplies, range from \$47.6 billion - \$113.1 billion (£30.27 billion and £707,905 billion)[98].

For the purposes of this research, the cost of security for the fuel used to run the diesel generator in Massawa is at the lower end of the range, and taken to be 2.4p/litre[99].

So, the total externalities due to use of diesel-powered generation at Massawa, is 2.5p/kWh of energy produced, and 2.4p/litre of diesel fuel used.

---

[96] This is based on an avoidance cost of 19€/ton of CO_2.

[97] This figure is based upon:

- 3.4p (total cost of coal externalities)–(benefit of CO_2 capture).
- The benefit of CO_2 capture =0.63 (portion of externalities associated with carbon dioxide production) x 0.9 (efficiency of CCS at removing carbon dioxide from exhaust) x 3.4 (total cost of coal externalities)) = 1.928 p/kWh benefit due to CCS CO_2 capture.

Therefore, 3.4 - 1.928 = 1.47p/kWh.

[98] There are other externalities associated with US petroleum use, including the Coast Guard and other municipal services, which bring the range of external costs associated with energy security paid by (predominantly American) taxpayers, up to \$78.215 billion - \$158.39 billion, or in specific terms between, \$0.214 and \$0.321/ US gallon.

[99] This is based on proportions presented in 'Gasoline Cost Externalities: Security and Protection services. An update to CTA's Real Price of Gasoline Report' that, \$78.215 billion to \$158.39 billion. equates to between \$0.214 and \$0.321/ US gallon.

6.6.2.1.1 *Volume of diesel fuel used.*

The volume of diesel fuel used over the 25-year life of the scenario was calculated based on the generator size to maintain the average power output for a year, plus an additional 25% to account for the 0.8 power factor (where only 80% of the power produced by the generator is useable).

The relationship between diesel fuel used and generator size, is shown below in Figure 96.

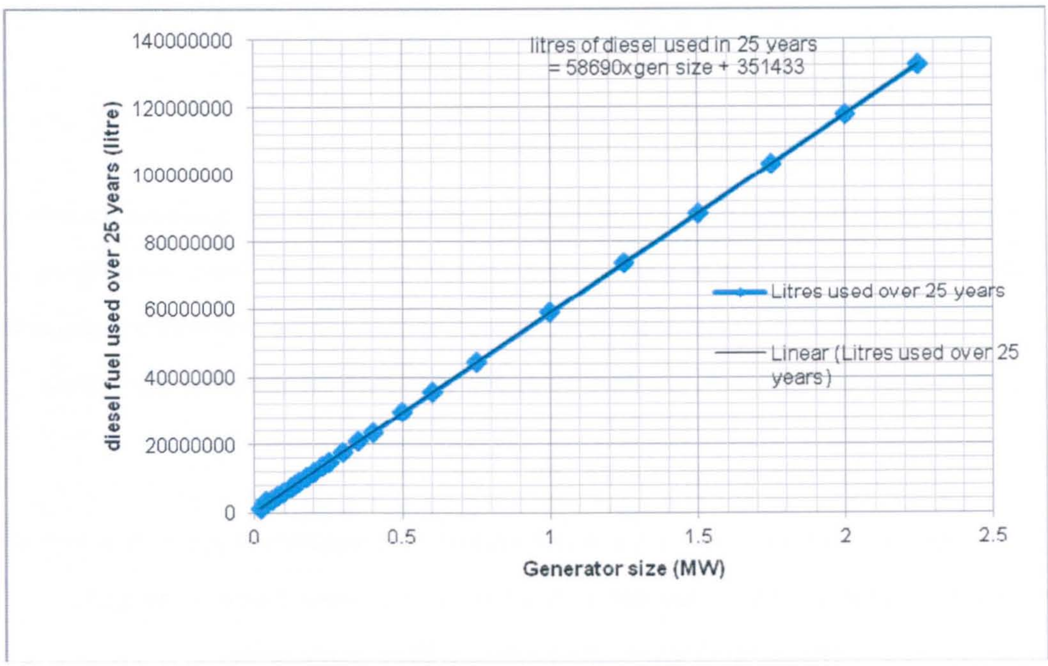

Figure 96: Diesel fuel used over 25 years, for varying generators sizes.

6.6.3 Costs associated with conventional power scenarios

Based on the information above, the following sections provide detail of the costs used to model conventional power scenarios with externalities. It is noteworthy that the external costs used are the most conservative costs available from the information available.

6.6.3.1 Massawa

The costs associated with the externalities of power production at Massawa using diesel generators over the 25-year life of the installation, are shown below in Table 56 for each of the RO plants being modelled.

Table 56: External costs associated with power production using diesel generators, at Massawa

	Total cost without externalities (($£x10^6$)	Additional cost due to externalities at £0.025/kWh of energy produced + £0.024/ litre of diesel fuel consumed over 25 years ($£x10^6$)	Total cost with externalities ($£x10^6$)
No BSR	231.7	102.4	334
Pelton Wheel	204.8	44.4	249
Pressure Exchanger	171.1	33.6	205

6.6.3.2 Newhaven

The costs associated with the externalities of power production at Newhaven using coal-fired plant with CCS over the 25-year life of the installation, are shown below in Table 57 for each of the RO plants modelled.

Table 57: External costs associated with power production using CCS at Newhaven

	Total cost without externalities ($£x10^6$)	Additional cost due to externalities at £0.0147/kWh over 25 years ($£x10^6$)	Total cost with externalities ($£x10^6$)
No BSR	211.7	8.98	221
Pelton Wheel	194.0	3.64	198
Pressure Exchanger	164.1	2.89	167

6.6.4 Differences due to externalities at each site

The difference in externality cost between the Massawa (diesel powered) and Newhaven (coal-fired plant with CCS powered) scenarios, can be seen above in Table 56 and Table 57. The externalities at Newhaven only increase the life cycle costs by four percent at most, but the Massawa scenario costs increase significantly, by almost 50% and 25%, for the No BSR and BSR scenarios, respectively.

6.6.4.1 Amount of power required at each site

The feedwater at Newhaven is cooler than at Massawa, which (as explained at Appendix B) means that more energy is required to make an equivalent amount of water as shown below in Table 58.

Table 58: Power used to produce water at Massawa and Newhaven

	Annual power used at Massawa (kWh)	Annual power used at Newhaven (kWh)	Percentage increase in power use at Newhaven (%)
No BSR	1.8×10^7	2.5×10^7	40
Pelton Wheel BSR	7.6×10^6	10×10^6	31
Pressure Exchanger BSR	5.8×10^6	7.9×10^6	38

When the increase in power required to produce water at Newhaven (between 31% and 40%) is taken into account, it is apparent that using a coal-fired plant with CCS, would be cheaper if applied at Massawa.

6.7 Results for comparison of technically-competent renewable energy scenarios, with conventional energy sources with externalities

Shown below in Table 59 and Table 60 are the results for the scenarios when externalities are applied at Massawa and Newhaven, respectively.

Scenarios that have become financially viable, (i.e. cheaper than the conventionally-powered equivalent) due to the application of externalities, are highlighted in yellow.

Table 59: Technically-competent and most financially-attractive scenarios at Massawa, when externalities are applied

Stage	Type of RO plant	Primary Power (MW)	Type of Secondary Power	Secondary Power (MW)	Hydrogen fuel used?	Ratio of renewable scenario cost to conventional	Ratio against conventional with externalities	Percentage difference (%)
1	No BSR	37.2	None	0	No	1.46	1.01	30.8
2	Pelton Wheel	21.8	None	0	No	1.694	1.392	17.8
	Pressure Exchanger	17.4	None	0	No	1.643	1.373	16.4
3	**No BSR**	**17.37**	**wind**	**9.93**	**No**	**1.227**	**0.85**	**30.7**
	Pelton Wheel	3.69	wind	14.68	No	1.353	1.112	17.8
	Pressure Exchanger	2.98	wind	12.41	No	1.423	1.19	16.4
	No BSR	15.82	wave	22.14	No	1.289	0.894	30.6
	Pelton Wheel	4	wave	12.53	No	1.286	1.057	17.8
	Pressure Exchanger	2.98	wave	12.15	No	1.273	1.064	16.4
4	No BSR	33.16	None	0	Yes	1.47	1.02	30.6
	Pelton Wheel	21.82	None	0	Yes	1.434	1.178	17.9
	Pressure Exchanger	17.39	None	0	Yes	1.402	1.172	16.4
	No BSR	9.69	wave	19.73	Yes	1.298	0.9	30.7
	Pelton Wheel	6.30	wave	9.85	Yes	1.23	1.012	17.7
	Pressure Exchanger	2.67	wave	8.14	Yes	1.212	1.013	16.4
	No BSR	13.45	wind	15.38	Yes	1.261	0.8746	30.6
	Pelton Wheel	*7.22*	*wind*	*7.43*	*Yes*	*1.189*	*0.9773*	*17.8*
	Pressure Exchanger	2.736	wind	4.69	Yes	1.226	1.024	16.5

Table 60: Technically-competent and most financially-attractive scenarios at Newhaven, when externalities are applied

Stage	Type of RO plant	Primary Power (MW)	Type of Secondary Power	Secondary Power (MW)	Hydrogen fuel used?	Ratio of renewable scenario cost to conventional	Ratio against conventional with externalities	Percentage difference (%)
1	No BSR	135.3	None	0	No	2.969	2.848	4.1
2	Pelton Wheel	66.5	None	0	No	2.525	2.479	1.8
	Pressure Exchanger	54.38	None	0	No	2.469	2.426	1.7
3	No BSR	20.5	wind	29.48	No	1.527	1.465	4.1
	Pelton Wheel	5.59	wind	14.12	No	1.38	1.355	1.8
	Pressure Exchanger	4.28	wind	13.72	No	1.358	1.334	1.8
	No BSR	20.5	wave	19.62	No	1.443	1.384	4.1
	Pelton Wheel	5.59	wave	7.63	No	1.196	1.174	1.8
	Pressure Exchanger	4.28	wave	6.33	No	1.188	1.168	1.7
4	No BSR	122.5	None	0	Yes	3.118	2.986	4.1
	Pelton Wheel	54.38	None	0	Yes	2.474	2.425	1.9
	Pressure Exchanger	45.37	None	0	Yes	2.371	2.327	1.7
	No BSR	13.72	wave	17.81	Yes	1.57	1.507	4.0
	Pelton Wheel	4.88	wave	6.67	Yes	1.209	1.187	1.8
	Pressure Exchanger	3.7	wave	5.47	Yes	1.204	1.184	1.7
	No BSR	14.67	wind	21.09	Yes	1.504	1.443	4.1
	Pelton Wheel	9.82	wind	8.825	Yes	1.265	1.242	1.8
	Pressure Exchanger	**3.475**	**wind**	**8.326**	**Yes**	**1.198**	**1.177**	**1.8**

6.7.1 Conclusion

6.7.1.1 At Massawa

As can be seen from Table 59 above, four of the six No BSR scenarios and one Pelton Wheel BSR scenarios have become financially viable due to the application of externalities. All of the scenarios are now within 40% of financial viability, and if the 'Stage 2' scenarios (Solar powered BSR RO plants) are discounted, the remaining scenarios are all within 20% of financial viability. The addition of externalities meant that the Pelton Wheel BSR, with wind power using hydrogen fuel (highlighted in '*italics*'), was displaced as the most financially attractive scenario, and replaced by the significantly less complex No BSR RO plant powered by solar and wind energy (highlighted in '**bold**').

6.7.1.2 At Newhaven

As can be seen from Table 60 above, the addition of externalities has not made any of the scenarios at Newhaven financially viable, due to the limited external costs associated with CCS, but it has given a slight improvement to their prospects, with the most financially-attractive scenario (Pressure Exchanger

BSR RO plant using tidal current combined with wave power, highlighted in bold text) now being less than 17% from financial viability.

6.7.1.3 Realisation of external costs

In reality, these external costs, especially those concerned with the potential impacts of climate change, cannot easily be applied to the cost of the conventional fuels, but there are initiatives, such as the 'clean development mechanism' (CDM)[100] available.

A specific requirement of the Kyoto Protocol[101] is that countries limit or reduce their greenhouse gas emissions. To help countries meet their emission targets, and to encourage the private sector and developing countries to contribute to emission reduction efforts, the Protocol included three market-based mechanisms, one of which was CDM.

CDM:

- Acknowledges the external costs of conventional fuels, and in particular those related to climate change impacts, and
- Allows developed countries to host carbon reduction Projects in developing countries, and use the carbon reduction from the project to meet their own carbon reduction targets.

That said, the administration of CDM is itself a cause for concern in many areas, including:

1. That the criteria for 'additionality' (demonstrating that the project would not have been viable without the additional support of the CDM), which is a cornerstone of the CDM is not always applied. So, other more obvious emission reduction projects, such as industrial gas and hydro projects, that are financially viable in their own right, or legacy projects that applied for the CDM retrospectively (i.e. CDM was not part of the decision making whether to progress with the project), may mean that although this type of project is ideal, it would not obviously be selected as it would appear to offer relatively low value.
2. That the administration and risk associated with CDM applications means that there is significant expense in lawyers, accountants, financiers, consultants, etc that would make a project of this type more (and potentially prohibitively) expensive to pursue. The proportion of the non-project related costs associated with a CDM project, which in some cases are more than 30%, are

---

[100] See http://cdm.unfccc.int/index.html for further details of the Clean Development Mechanism (CDM). [Last viewed on 7 August 2011].

[101] The Kyoto Protocol is an international agreement that sets binding targets for 37 industrialised countries and the European community for reducing greenhouse gas emissions until 2012. Greater detail of the Kyoto Protocol is available at http://unfccc.int/kyoto_protocol/items/2830.php [Last viewed on 7 August 2011].

highlighted within 'The Cost Efficiency of Offsetting through the CDM' [Carbon Retirement Limited, 2009].

3. That the Kyoto Protocol upon which CDM was based was only agreed until 2012 and at the time of drafting this thesis, the lack of agreement regarding the extension of the Kyoto Protocol beyond 2012 bought the legal premise of CDM beyond 2012 into doubt. The situation is described in more detail at the Carbon Solution Credit website [Carbon Solution Credit, 2012].

Many of these issues are explained in greater detail in 'Is the CDM fulfilling its environmental and sustainable development objectives? An evaluation of the CDM and options for improvement' [Schneider, 2007] and 'Effects of the CDM on Poverty Eradication and Global Climate Protection' [Rubbelke and Rive, 2008].

These issues though are primarily focussed on the administration of a global incentive that has traditionally suffered from the required lack of the global census, and due to its novelty and the nature of the incentive that it tries to offer will always present a lucrative income stream for some. One would hope that in the future, the appropriate long-term consensus and appropriate standards of administration and compliance are achieved to allow the CDM to meet the aims and objectives that it was designed for more effectively.

On the national level, the UK has introduced fiscal incentives such as the Renewable Obligation Certificates (ROCs) and the Feed-in Tariff (FIT), which was introduced in 2010, and provides:

- Payment for all the electricity generated from small scale low carbon sources
- Additional payment for generated electricity that is exported to the grid, and
- Savings on energy bills due to using energy that has been generated locally reducing the amount of energy imported from the grid.

Shortly after its introduction, and having achieved its aim of encouraging uptake of solar PV power, the UK government announced that the tariff would be cut almost immediately to reflect the lower cost of solar power installation that mass production and take-up (encouraged by the introduction of FITS) have caused in the UK. This proposed tariff reduction has been challenged in the courts by the solar power companies, who experienced almost 90% reduced installations (including many cancellations of existing orders), and the government lost the ruling and at the time of drafting are facing demands for £2.2 million in compensation for having:

> *"caused major financial losses and materially harmed the confidence of both consumers and the industry"* [Vaughan, 2012].

Once again, it is noteworthy that a well intentioned fiscal policy needs to be introduced and administered very carefully if it to avoid falling foul of the market forces that it is attempting to incentivise.

6.7.1.4 Social Entropy and Dissipative Structures

In general, as an interpretation of social entropy and dissipative structures[102], energy and order are drawn towards wealth and urban concentrations, and the corresponding waste and disorder are exported to those with the least political power in the social-geographical peripheries.

This is apparently the case in most of the developing world, including Eritrea, which has had its destiny dictated by external factors and internal disorder. It is these points (highlighted by lack of infrastructure, susceptibility to the impacts of climate change, etc) that provide the compelling need for a dedicated and local secure clean water supply to enhance the local order.

It is the relatively disordered local conditions (lack of power infrastructure and relatively high imported diesel prices, etc) that mean that there is the potential for a variety of renewable powered scenarios, but in particular solar and wind-based scenarios, to compete very favourably with the diesel generator-powered equivalent situation over the 25-year lifecycle, once the externalities of using diesel fuel are acknowledged.

It is in spite of the logic of the dissipative structure, the solution (moving away from the normal relatively-disordered state of equilibrium, using renewables to power reverse osmosis plant) can be achieved without exporting disorder (depriving/ undermining others) by using the least complex scenarios, which are relatively easy to operate and maintain.

That said, the combination of an RO plant with hybridised combination of solar and wind power is, although one of the least complex scenarios, still relatively complex. As such, this scenario will require a through understanding of operability and maintenance, if it is to be effective.

6.7.2 Ability of scenarios to meet water demand profile

To allow a measure of the effectiveness of the RO plant, a simple relationship of the impacts due to reduced flowrates was developed and is shown below in Figure 97.

[102] Social entropy
Another aspect of providing for human need is that the management of the needs of one group, has the potential to undermine that of another group to maintain order in their society.
Dissipative structures are systems, which stay far from equilibrium by continually drawing in exergy (negative entropy) from the outside world, and exporting the entropy, or disorder they produce in the process. Erwin Schrödinger, on page 79 of 'What is Life?' (Cambridge University Press, 1967), suggests that the device by which an organism maintains itself stationary at a fairly high level of orderliness (= fairly low level of entropy) really consists of continually sucking orderliness from its environment. 'This interpretation can be extended from biological to social systems. Societies also maintain their internal structure by drawing order from their environments. For hunter-gatherers, this is generally a matter of exploiting other species in a fairly local, ecological context. For cities or world system centres, however, the maintenance of structure relies on exchange with other, peripheral social sectors, more directly involved in the extraction of exergy from nature.

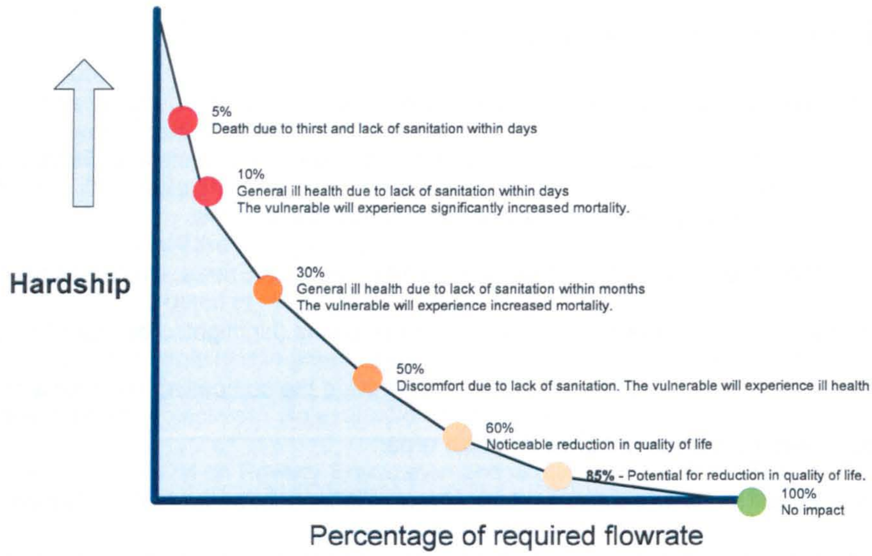

Figure 97: Impact on human health of varying degrees of water shortage

Figure 97 above indicates the impact on human health, expected hardship, and required external intervention points at reduced levels of water production from the RO plant in terms of the proportion of maximum design delivery. Based on this model, no action would be taken until water production fell below 85% of the full flowrate.

If a methodology of this type were to be implemented, the identification and reaction to flowrates below 85% would need to be developed using the drought plan methodology as explained at the Environment Agency website[103].

6.7.2.1 Model of water use to be adopted

The daily water use was derived based on assumptions about daily activities[104], and used to define the daily water requirement from the RO plant. For simplicity no seasonal variations were included in the daily water usage cycle, which is shown below in Figure 98.

---

[103] Environment Agency website at http://www.environment-agency.gov.uk/homeandleisure/drought/31771.aspx [Last viewed on 7 August 2011].

[104] The water uasage profile can be explained as follows:

- Low water use from midnight until 05:30 when people start to get up in the morning, make tea or coffee, run a bath or have a shower.
- Water use activity carries on through the day with washing machines being used, dishes being washed, lunches prepared, but most water is used in the morning.
- In the afternoon there is a slight reduction in water consumption as people go out, but from 16:00 onwards, consumption increases as supper is prepared, gardens are watered, and children are bathed. The water consumption then reduces in the late evenig, as people go to bed.

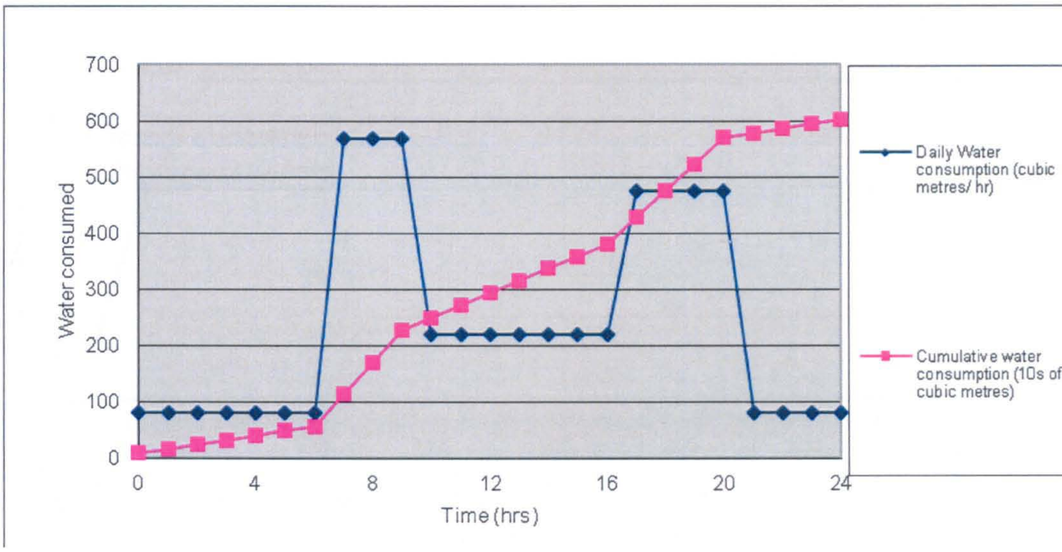

Figure 98: Daily water usage cycle

This profile consumes 5950m^3 of water over a 24hour period, which equates to 85% of the required daily consumption.This is the minimum water consumption before intervention to manage the lack of water, is implemented.

The water produced by the RO plant is demanded by local users according to a specific usage profile, shown above in Figure 98. Although in reality, the implementation of a Project of this type would require a transition from the old water source to the new, which would mean that the reservoir would be adequately stocked, the assumption was made for this research that water would be delivered and extracted from an empty reservoir, which would accumulate water as supply exceeded the user's demands, as the year progressed.

The most financially-attractive scenarios at each site were:

Massawa – No BSR RO plant, powered by solar and wind power

Newhaven – Pressure exchanger BSR RO plant, powered by tidal current and wave power.

The water produced by the RO plant in these scenarios was modelled against the daily use profile, shown above in Figure 97, and the resulting cumulative shortfall is shown below in Figure 99.

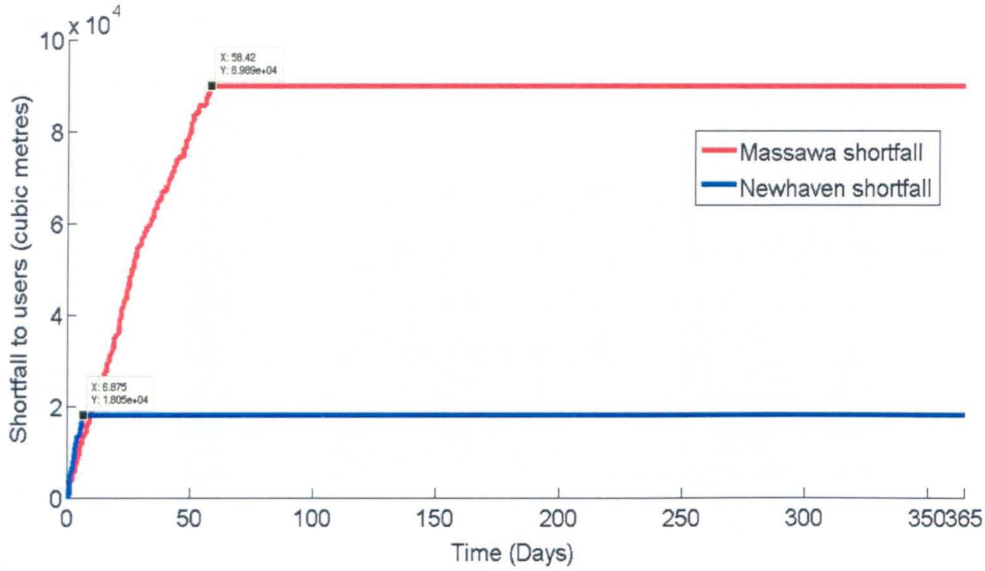

Figure 99: Shortfall in water supply to users for most financially viable scenarios at Massawa and Newhaven

As can be seen from Figure 99, there is a shortfall at both sites for a period of time at the start of operations, but once this shortfall period is passed, and the reservoir is partially filled, (when the plot levels off), there are no shortfalls to local user's water demands. At Massawa the shortfall is estimated as 89890m^3, which is around 3.5% of annual water demand. The period of disruption, where the water required by the local users is not available at the time of demand, is expected to occur between the start and almost 2 months into operation. At Newhaven, this shortfall was significantly less at 17870m^3, (around 0.7% of annual water demand), and the disruption lasted less than one week from the start of operation.

If the RO plant is started on 1 January as modelled, this shortfall equates to an additional requirement for:

- Almost 13 days of water production at Massawa, and
- Around 2.5 days of water production at Newhaven.

There is however, the option to start the facility at different times of the year to make better use of the prevailing energy production conditions. Figure 100 and Figure 101 below show the changes in shortfall due to starting the operation at the start of each consecutive month for Massawa and Newhaven respectively.

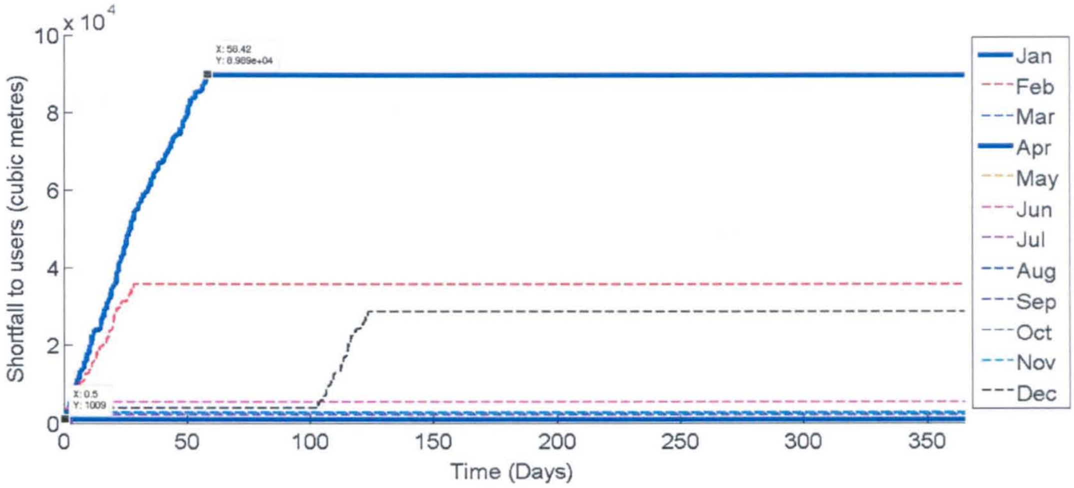

Figure 100: Shortfall to users at Massawa, due to starting operations at different times

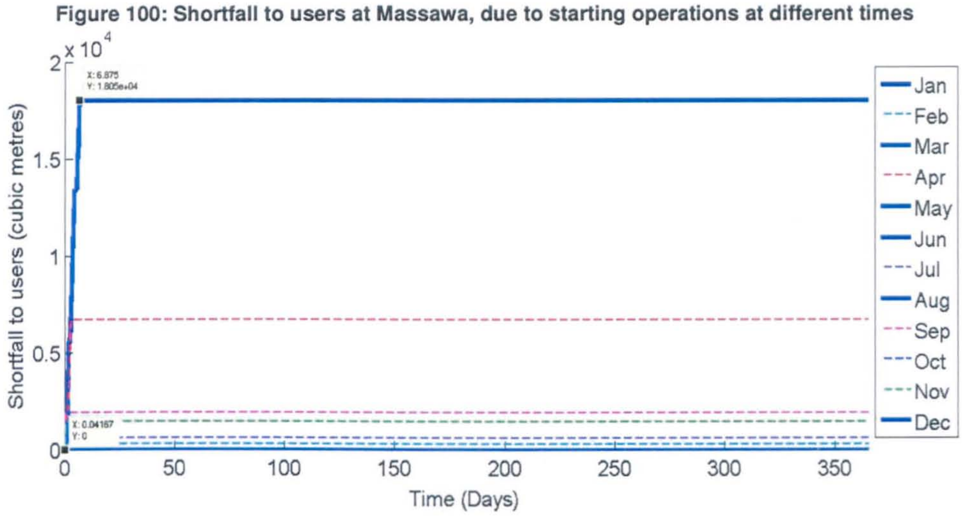

Figure 101: Shortfall to users at Newhaven, due to starting operations at different times

As can be seen from Figure 100 and Figure 101 above, starting the RO plant at different times of the year has a considerable effect on the ability of RO plant to produce the water demanded by the local users at the time it is required. At Massawa, the deficit reduces from almost 90,000m^3 and 60 days of disrupted supplies if started in January, to just over 1000m^3 with half a day's disrupted supply if started in April. At Newhaven, if the RO plant is started at the beginning of March, May, June, August or December, there will be no shortfall or periods of disrupted supply.

Therefore, it was considered that the most financially-attractive scenarios at each site could meet the water requirements of the local users demand profile, but to achieve this, the most appropriate start time will need be identified, if the reservoir is empty at the start of operation.

This said, it is also apparent that the seasonal fluctuations in water production due to the power available to operate the RO plant, and the changing demand for water, could have an impact on the scenario's ability to meet the user's demands for water. As such it is considered that mitigation of seasonal water production and use impact risks would need to be investigated further if these scenarios are to be implemented.

This mitigation may involve ensuring that additional water is available in the reservoir to compensate for seasonal fluctuations.

7 NPV

The **net present value** (NPV) or **net present worth** (NPW) of a time-based series of cash flows, both incoming and outgoing, is defined as the sum of the present values (PVs) of the individual cash flows. In the case when all future cash flows are incoming, and the only outflow of cash is the purchase price, the NPV is simply the PV of future cash flows minus the purchase price. NPV is a central tool in Discounted Cash Flow (DCF) analysis, and is a standard method for using the time value of money to appraise long-term Projects. As such it was applied within this research, as it would be an integral part of the decision whether a particular option was:

- Viable, and/ or
- More or less viable than another option.

Each cash inflow/ outflow is discounted back to its present value (PV). Then these are added together. So, NPV is the sum of all the terms:

$$Rt/(1+i)^t$$

where:

t - The time of the cash flow.

i – The discount rate (the return that could be earned on an investment in the financial markets with similar risk.); the opportunity cost of capital.

Rt - The net cash flow (the amount of cash, inflow (value of water sold) minus outflow (the cost to maintain the power source and RO plant) at time *t*.[105]

The following sections will derive the Price of water and Discount Rate to allow the NPV to be calculated.

7.1 Price of water

The price of water was assessed on the basis that it would be the income stream that would offset the cost of the RO plant, power installation and reservoir.

The cost of water at Newhaven is relatively well understood, at £1.04/m^3 (southernwater.co.uk) 2012[106], but the cost of water at Massawa is less clear.

[105] Any cash flow within 12 months was not discounted for NPV calculations.

[106] Taken from the Southern Water website available at http://www.southernwater.co.uk/DomesticCustomers/aboutYourBill/default.asp [Last viewed on 7 August 2011] and based on a metered supply.

'Designing Cost-Effective Sea Water Reverse Osmosis System under Optimal Energy Options for Developing Countries' [Gilau and Small, 2006], states that Eritrea water production and tariff costs are about $0.30/m^3 and $0.43/m^3 (£0.1908 and £0.2735) respectively, giving a total cost of around £0.46/m^3. This is compared with 'Identification and evaluation of reuse-oriented sanitation concepts in African Urban Areas Case study: Massawa, Eritrea' [de la Pena, 2006], also from 2006, which presents a maximum water tariff cost of 8 Nakfa/m^3 for large industrial installations, which equates to £0.33/m^3.
The RO plant at Massawa is designed to produce water fit for direct human consumption, and the water costs quoted above are for normal municipal supplies, which according to 'Worldwide Movers' are not fit for direct human consumption [Worldwide Movers, 2011].
As part of an informal telephone conversation, Michael Tesfai[107], from the Eritrean Embassy, stated that municipal water in Eritrea costs less than 5p/ litre (£50/m^3), and bottled drinking water costs less than 10p/litre.
The Asmirano Report, 'Eritrea's 20th Anniversary Comprehensive Report Card' [Hagos, 2011] states that:

> *'... most urban areas [in Eritrea] do not have municipal water piped directly to their homes and are at the mercy of the owner of water tankers that visit areas at their whim at unscheduled times... .'*

The Munich Re Foundation website [Munich Re Foundation] also states that:

> *'Water from tank trucks costs 15 Nakfa or about €0.90 per 20-litre canister'.*

This equates to 3.8p/litre or £38/m^3, which is in keeping with Michael Tesfai's estimate of less than 5p per litre or £50/m^3. The Munich Re Foundation article talks specifically about water delivery to an outlying region and states that:

> '[a 20 litre canister costs] *nearly a half a day's wages... .'*

For the purposes of this research, the cost of water to the end user at Massawa was taken as £38/m^3, based on the estimate from the Munich Re Foundation, as the first two estimates were at least 5 years old at the time of drafting.
This estimate is taken to include water collection, storage and transportation, and water truck maintenance costs.
The RO plant will, in effect, only be a different water supply point for the tankers to collect water from, so cannot be given credit for the full £38/m^3 that the end user pays.

[107] Michael Tesfai is a member of staff at the Eritrean Embassy in London. The telephone conversation took place on the morning of 15 September 2011.

It is noteworthy that this cost is beyond the reach of most Eritreans and according to 'Asmara, Africa's Secret Modernist City' [Gebermedhin, 2007], discussing the water limitations on Asmara (the Eritrean capital city):

> *'Households at the lower level of income consume, on average, only 15-18 litres per capita per day. This amount is close to the WHO minimum requirement below which it would be difficult to maintain adequate sanitation.'*

It is not clear to the external observer how much water costs in Massawa, but it is clear that the costs associated with the logistics of water delivery, (and perhaps the desire to make a healthy profit), makes water so expensive that its availability is limited to the extent that, for some, their health could be affected.

The overall cost for the most financially-attractive scenario at Massawa is around £280Million over 25 years, and to break-even each cubic metre of water delivered by the RO plant would need to be priced at £4.43, which is still more than four times the cost of water at Newhaven.

For the purposes of this research, the cost of the water delivered at Massawa was taken to be £4.43.

The indicative costs of water supplied at Massawa and Newhaven are shown below in Table 61.

Table 61: Cost of water in Massawa and Newhaven

	Massawa	Newhaven
Cost of water (£/m^3)	4.43	1.040
Total (£x10^6/year)[108]	11.32	2.66
Cost per person per year based on user group of 50,000 people. (£)	226.37	53.14

7.2 Discount rate

For economists, calculation of future costs and benefits routinely involves a discount rate.

The logic of discounting starts from the fact that money today is worth more than the same amount of money in the future.

To express current and future costs and benefits on a comparable basis, economists discount future amounts, converting them to the equivalent present value.

The implication of the discount rate, in this case, is that it is the minimum return that would be economical considering how the finance for the Project is being provided. If the capital for the Project is personal savings, one might be satisfied with the interest that could be earned from those savings over the next 25 years, say 5%/year. If the finance is held by a company that is evaluating their capital budget, the discount rate would reflect the highest return from the money if it were invested, including the cost of

[108] Based on 2555000m^3 of water produced per year (7,000m^3/day x 365days).

money or the interest rate required to borrow money, which might be 4 - 4.5% according to Santander estimates[109]. Then there would be a further addition to represent the company's expectation for inflation. It might be decided that a company or organisation would not accept any project that does not give a positive net present value with a 10% discount rate to account for all the uncertainty associated with the 25-year term of a Project of this type.

It is assumed that this type of Project would need to be financed as a public amenity by a large corporate entity, or government. The normal method for calculating the discount rate for UK government financed infrastructure Projects is 3.5%[110] above the inflation rate (which in this case is taken, conservatively, as 3.5%[111]) [Bank of England, 2012] as described in the UK Treasury's 'Green Book' [HM Treasury, 2011]. For the purposes of this research, the discount rate was taken as 7%.

7.3 NPV Results

Shown below in Figure 102 and Figure 103, are the NPV results for Massawa and Newhaven, respectively.

[109] This is based on the fixed rate mortgage rate from Santander for loans up to £1,000,000 available at https://www.santander.co.uk/csgs/ContentServer?appID=abbey.internet.Abbeycom&c=Page&canal=CABBEYCOM&cid=1237884262478&empr=Abbeycom&leng=en_GB&pagename=Abbeycom%2FPage%2FWC_ACOM_TemplateG [Last viewed on 7 August 2011].

[110] The 3.5% is made up principally of two elements – the social time preference for having benefits sooner rather than later, which is put at 1.5%, added to the rate of *per capita* growth in the economy. This growth rate is put at 2%, based on a past real growth rate of 2.1% *per annum* in the period 1950 to 1998.

[111] The Bank of England stated that the Consumer Price Index (CPI) rate of inflation was 3.5% in March 2012 although it had reduced considerably from a peak of 5.2% in September 2011. 3.5% is considered to be a conservative estimate.

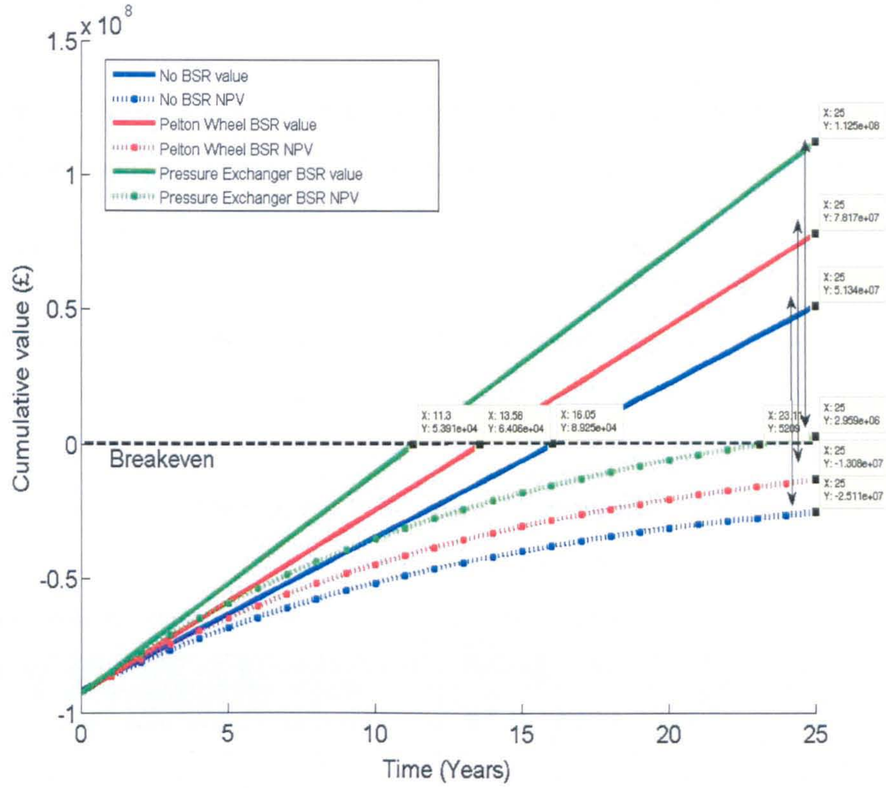

Figure 102: Comparison of the value of conventionally powered scenarios at Massawa with and without NPV at 7% discount rate.

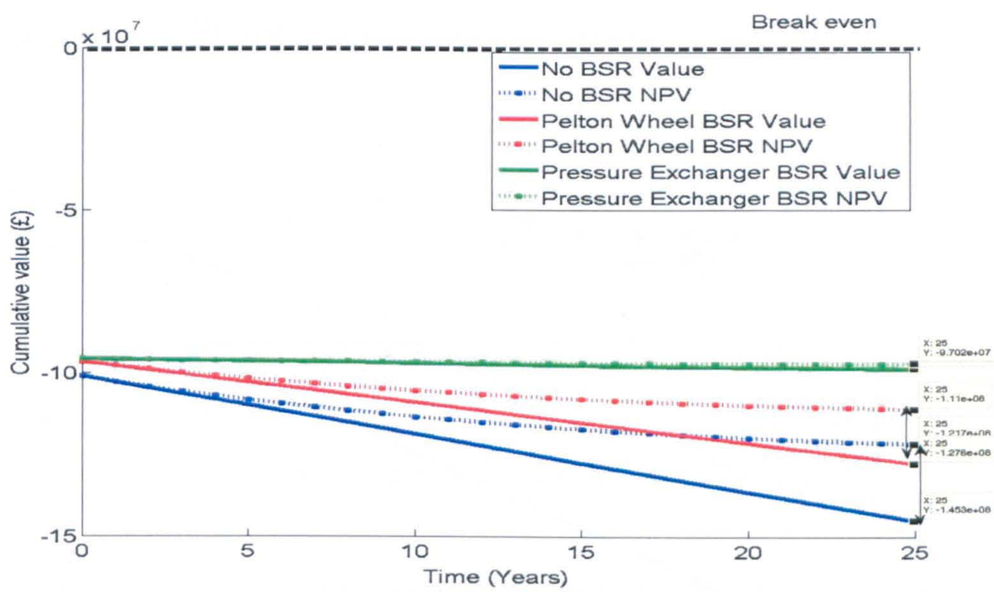

Figure 103: Comparison of value of conventionally powered scenarios at Newhaven with and without NPV at 7% discount rate.

It is noteworthy that:

1. All of the conventionally-powered scenarios at Massawa are financially viable when the water cost of £4.43/m^3 is employed:

- Breaking even between 11 and 16 years, and

- Delivering between £50 million and almost £113 million profit at the end of the 25-year life cycle.

2. The only conventionally powered scenario that is financially viable when the NPV methodology is applied is the Pressure Exchanger BSR, and profits in the order of £113 million are reduced to less than £3 million.
3. NPV methodology reduces the value of future money (including losses), and
4. As can be seen by Figure 102 above, the scenarios that were making an annual profit have had this profit reduced to the extent that, they do not, or barely break even, over the 25-year life of the installation.

As shown in Table 62 below, this discounting to indicate NPV, as opposed to PV, equates to differences of tens of millions of pounds over the lifetime of the scenarios.

Table 62: Difference between Cash flow Values and Discounted NPV after 25 years, for conventionally powered scenarios

	No BSR (£x10^6)	Pelton Wheel BSR (£x10^6)	Pressure Exchanger BSR (£x10^6)
Massawa	76	91	110
Newhaven	24	17	1.6

7.3.1 Break-even point for most financially attractive scenario

Shown below in Figure 104 is the cumulative value for the most financially attractive renewable powered scenario at Massawa (Solar plus Wind power)[112], and the equivalent No BSR RO plant Diesel Generator-powered scenario.

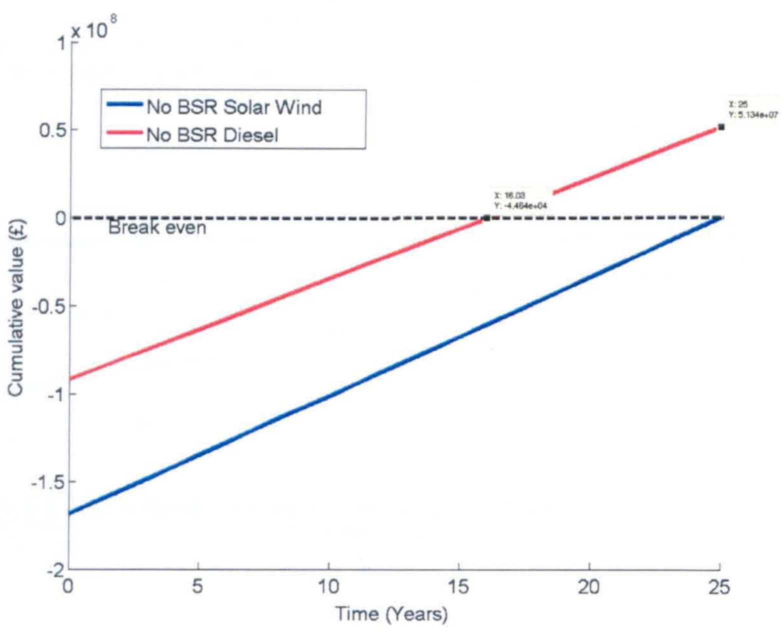

Figure 104: Comparison of value of most financially-attractive renewable and conventionally-powered scenarios.

[112] This scenario was selected for further investigation as it is the most financially-attractive of all the scenarios modelled. It is made up of 17.34MW of solar power plus 9.93MW of Wind Power, giving a total installed power of around 27.3MW.

Having set the price of the water at the cost for break-even of the renewable-powered scenario, it is shown to break-even at the 25-year point, and the diesel generator powered scenario makes a profit of over £50 million over the life of the installation.

When the externalities associated with diesel generator use are applied (amounting to just over £102 million over the 25 years of the installation) the profitability of the solar plus wind scenario changes such that it is viable as shown below in Figure 105.

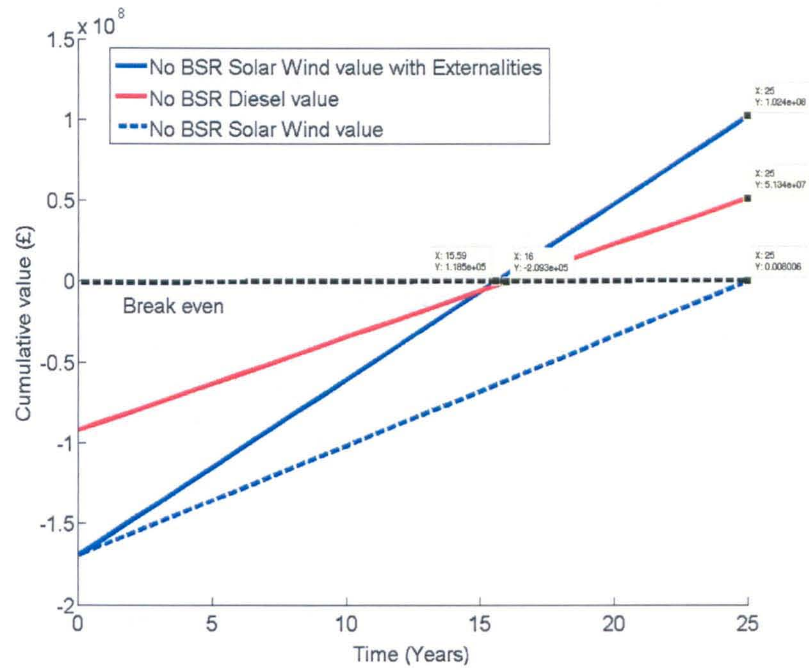

Figure 105: Comparison of value of the solar and wind scenario with diesel generator with externalities of diesel use applied.

As can be seen from Figure 105 above, with the application of the externalities associated with diesel generator use, the solar plus wind scenario:

- Breaks into profit at around 16 years, which is almost exactly the same time as the diesel generator scenario, and
- Ends the 25-year life of the installation with over £102 million in profit, which is the value of the externalities applied.

This situation changes significantly when the NPV methodology is applied, as shown below in Figure 106.

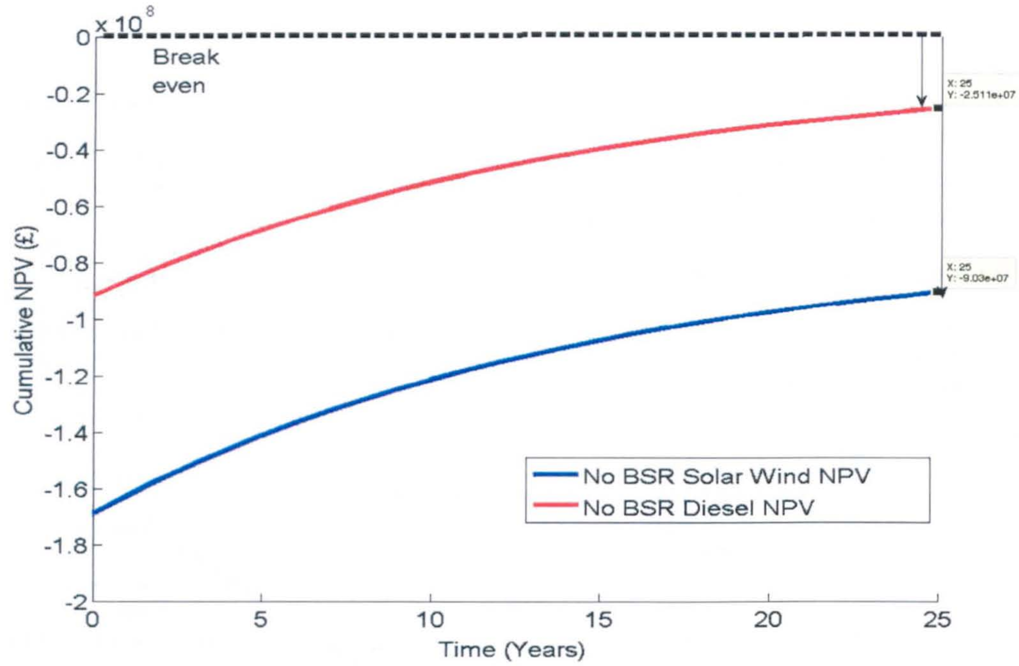

Figure 106: Comparison of the NPV of the solar and wind scenario with diesel generator with externalities of diesel use applied.

As can be seen from Figure 106 above, the application of the NPV methodology alters every aspect of the financial viability of the renewable powered scenario, in that:

- It no longer breaks into profitability
- It no longer breaks-even with the diesel generator scenario
- The end-of-life profit of around £102 million has now turned into a loss of more than £90 million, and
- The profit difference between the solar plus wind, and diesel-powered scenarios has reduced from £50 million to a loss of around £65 million.

7.3.2 Discount rate revisited

In selecting the appropriate discount rate for long-term public policy decisions, economic theory tends to distinguish between two components:

- The rate of pure time preference, and
- The wealth-based component of the discount rate.

The *rate of pure time preference* is the discount rate that would apply if all present and future generations had equal resources and opportunities.

In addition, there is a *wealth-based component* of the discount rate, reflecting the assumption that if future generations will be richer than we are, then there is less need for us to invest today in order to help them protect themselves.

In the notation of the Stern Review [Stern, 2007], the discount rate, 'r', is the sum of these two parts:

$$r = \delta + \eta g$$

where:

δ (delta) is the rate of pure time preference

g is the growth rate of *per capita* consumption. If *per capita* consumption is constant, implying that $g = 0$, then the discount rate $r = \delta$.

η (eta), determines how strongly economic growth affects the discount rate. A larger value of η implies a larger discount rate, and hence less need to provide today for future generations (as long as *per capita* consumption is growing).

Stern takes the position that all future generations should be treated equally, except that there is a small probability that future generations will not exist – for example, if a natural or anthropological disaster destroys most, or the entire human race. The probability of destruction of humanity is taken by Stern as 0.1% per year; pure time preference (δ) is therefore set equal to 0.1%. That is, Stern suggests that, we are only 99.9% sure that humanity will still be here next year, so we should consider the well-being of people living next year to be, on average, 99.9% as important as that of people living today. Stated simply, the only reason that the current generation should not consider the needs of those in the future is due to the small possibility that the future generation will not exist, not because the future generation will be rich enough to manage the previous generations' impact on the environment.

To calculate the discount rate, Stern estimates that the growth of *per capita* income will average 1.3% per year, and sets $\eta = 1$. Therefore, the Stern Report discount rate is:

$$r = \delta + \eta g = 0.1\% + (1 \times 1.3\%) = 1.4\%$$

This is obviously significantly lower than the 7% employed based on the notion of the installation being financed as a capital investment Project, and makes a marked difference to the viability of the scenario, as shown in Figure 107 below.

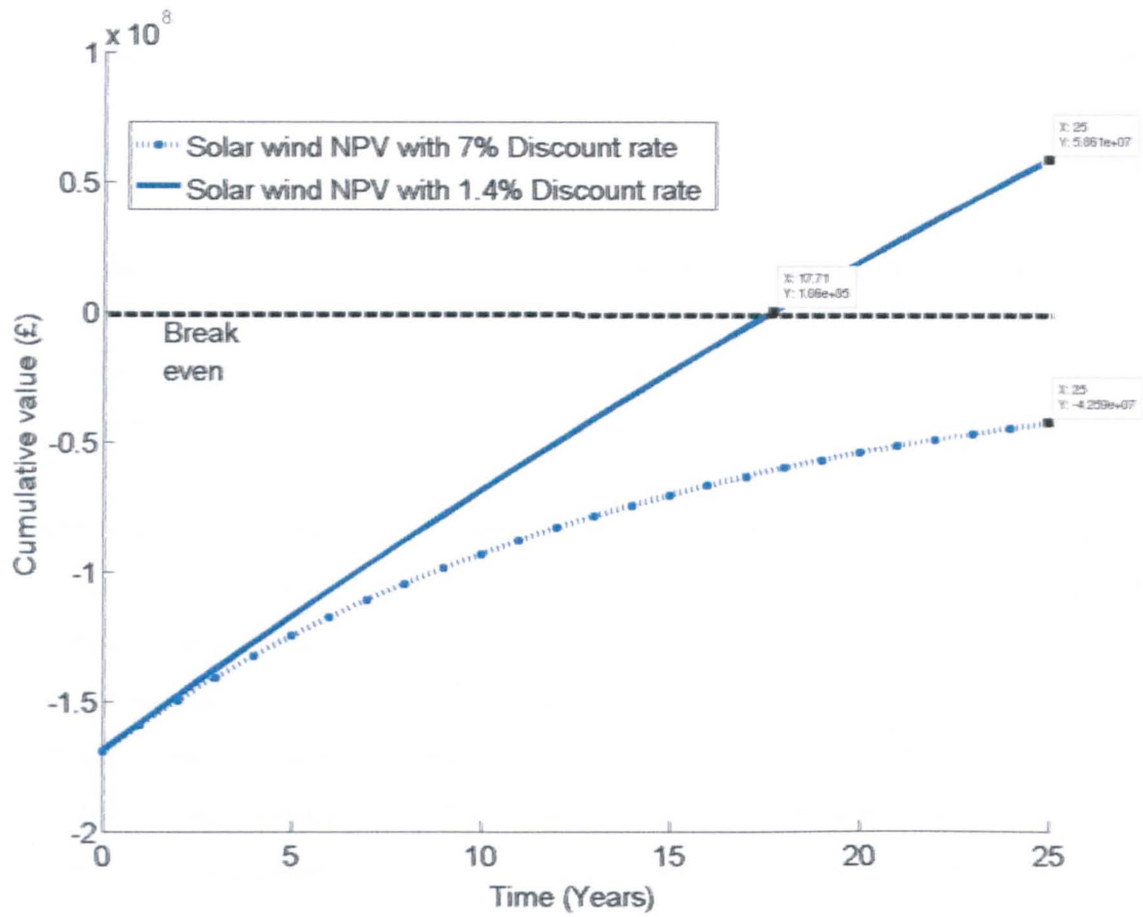

Figure 107: Comparison of the solar and wind scenario NPV, with 7% and 1.4% discount rates

As can be seen from Figure 107 above, the reduction of the discount rate means that the solar plus wind scenario breaks even in less than 18 years, and makes a profit of over £58.5 million over the 25-year life of the installation.

Although the application of such a reduced discount rate is not justifiable for a commercial concern, as it reflects savings to future generations, (which they cannot physically pay in advance), it is clear that:

- The discount rate has such a large impact on the financial viability of the scenario, and
- It is worth considering the application of the Clean Development Mechanism (CDM) or local incentive initiative to properly acknowledge the hidden benefits of:
    - Not delaying implementation of Projects of this type, and
    - Reducing the burden of climate change on future generations.

8 Scrutiny

This section:

- Assesses the impact of the modelling on the accuracy of the results
- Assesses the variables that are most likely to impact on the viability of scenarios, and
- Identifies changes to the scenarios modelled that could impact on their viability.

8.1 Impact of modelling on accuracy of results

8.1.1 Assessment of accuracy of RO plant profiles

This section provides an indication of how accurate the modelled RO plant operating profiles are, when compared to actual 'real world' RO plants. The detail of how the modelled RO plant profiles were derived is available in Appendix B.

The specific power consumption profiles are shown below for the modelled No BSR, Pelton Wheel BSR and Pressure Exchanger BSR RO plants, in Figure 108, Figure 109, and Figure 110, respectively, with their optimum water production profiles.

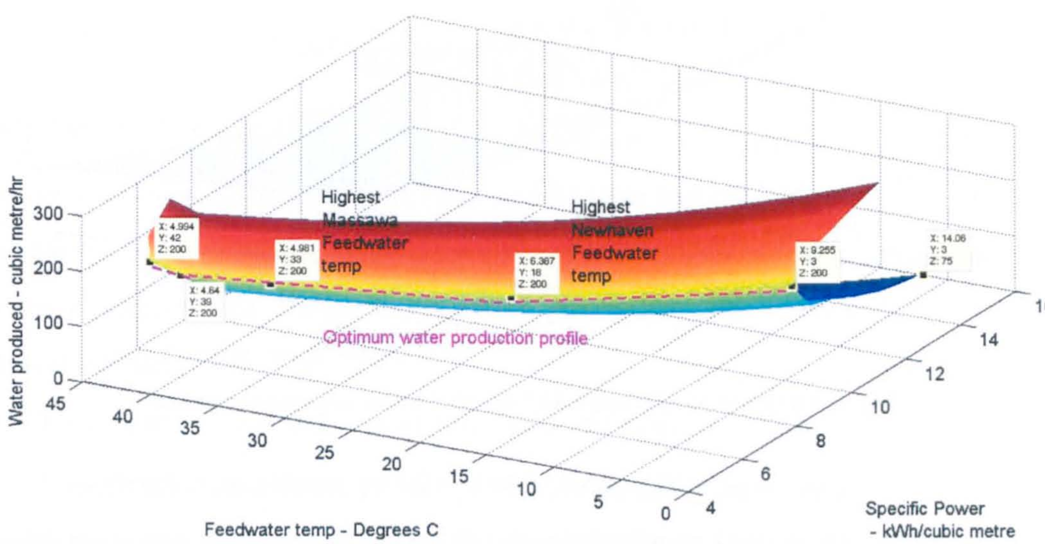

Figure 108: No BSR RO plant power consumption profile

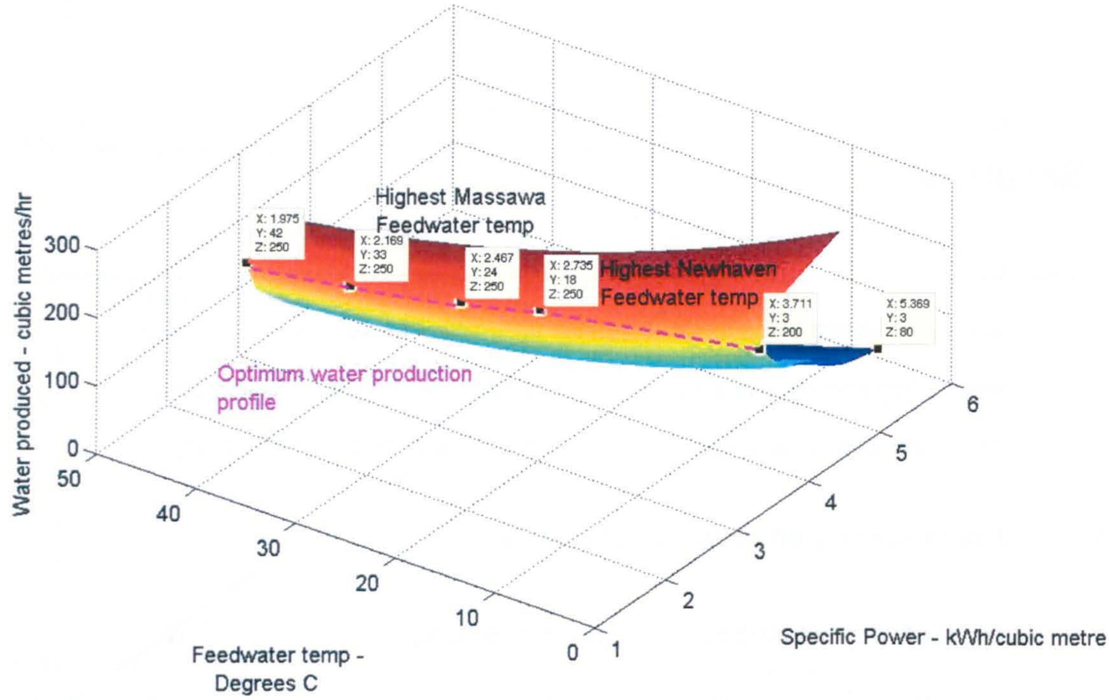

Figure 109: Pelton Wheel BSR RO plant power consumption profile

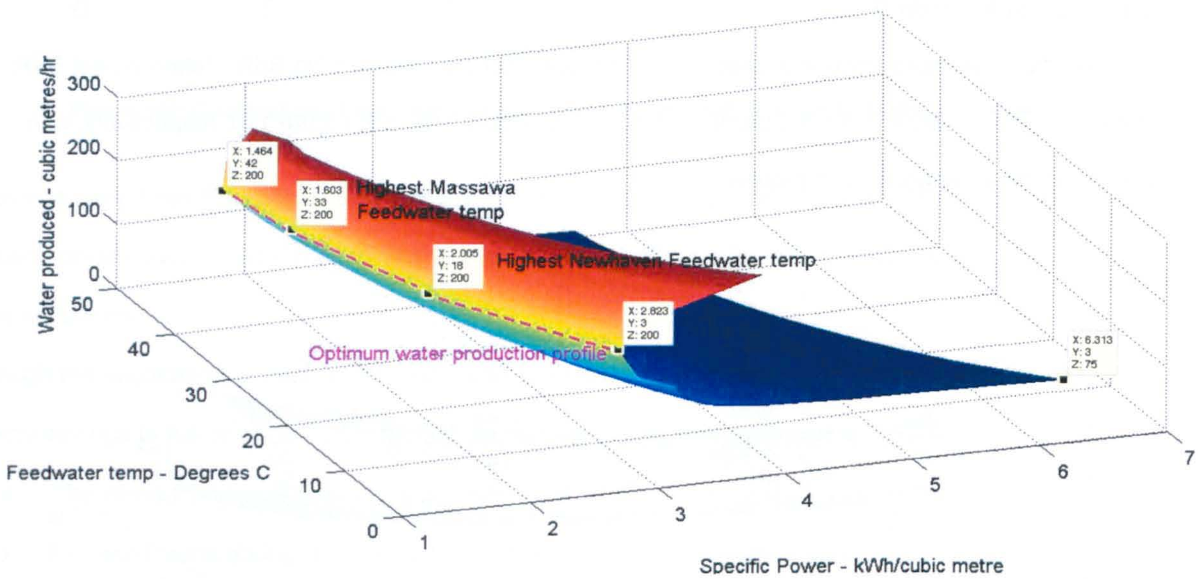

Figure 110: Pressure Exchanger BSR RO plant power consumption profile

These figures indicate, unsurprisingly, that the most efficient water production occurs at higher temperatures. Also shown above in Figure 108, Figure 109 and Figure 110 are the best specific power consumption rates modelled at each site, based on the highest feedwater temperatures (33ºC and 18ºC, for Massawa and Newhaven, respectively).

These are consolidated in Table 63 below.

Table 63: Comparison of modelled RO plant and real world RO plant power consumption

Type of RO Plant	Real world data		Modelling data	
	Normal expected range (kWh/m^3)***	Most efficient (kWh/m^3)	Most efficient at Massawa 33ºC (kWh/m^3)	Most efficient at Newhaven 18ºC (kWh/m^3)
No BSR	4 – 7		5.0	6.4
Pelton Wheel	3.1 – 5.9	2.7*	2.2	2.7
Pressure Exchanger	2.2 – 3.1	1.7**	1.6	2.0

* Taken from 'Energy Recovery in Caribbean Seawater Reverse Osmosis [Stover and Cameron, 2007]

**Taken from 'Energy recovery devices help lower cost of RO Desalination [Stover, 2007].

*** Taken from 'SWRO Energy Recovery Technology Shatters Design Barriers' [MacHarg, b].

8.1.1.1 No BSR

All specific power consumption figures for the No BSR model, are within the range expected for this type of RO plant, so for the purpose of this research, are taken as correct.

8.1.1.2 Pelton Wheel BSR RO plant

The model is optimistic for the Pelton Wheel BSR RO plant, but it would seem reasonable that the warm waters of Massawa would deliver some benefit above the normally expected range. So, for the purposes of this research, an error of +10% was applied to the modelled data, at both Massawa and Newhaven to account for the over estimation of efficiency.

8.1.1.3 Pressure Exchanger

The model is also slightly optimistic for the Pressure Exchanger BSR RO plant, and (as for the Pelton Wheel) it would seem reasonable that the warm waters of Massawa would deliver some benefit above the normally expected range. The increase in efficiency for the Pressure Exchanger BSR RO plant is less than that of the Pelton Wheel, with:

- The best efficiency at Massawa being just below the most efficient case, and
- The most efficient at Newhaven being above the most efficient.

So, for the purposes of this research, an error of +5% was applied to the modelled data at Massawa to account for the over estimation of efficiency, and the profile for Newhaven was taken as correct.

8.1.2 Impact of the use of polynomials on the accuracy of the results

The fitting of polynomials to data values and modelled results was extensive within this research, and so it is likely that there is a potential error between the 'real' data and the results obtained. It is noteworthy that there is also a degree of error associated with explicit and implicit working assumptions used within this research. The impact of these working assumptions on the results has not been calculated, due to time constraints.

The main areas where polynomials were employed were:

- Feedwater temperature
- Power used (particularly for the variability of pumping efficiency at varying loads)
- RO plant operating profiles, and
- Renewable power inputs.

R^2 (or the coefficient of determination) is used within this section, which ranges in value from 0 to 1. It is the square of R (the correlation coefficient), which ranges in value from -1 to 1 where:

> A value of 1 implies that the modelled data represents the actual data exactly, and could be described by a straight line graph with all data points lying on that line for which Y increases as X increases.
>
> A value of -1 implies that the modelled data represents the actual data exactly, and could be described by a straight line graph with all data points lying on that line for which Y decreases as X increases.
>
> A value of 0 implies that there is no linear correlation between the modelled and actual data.

The error value returned by the Excel spreadsheets is R^2, and for the purposes of this research, the square root of this value was calculated to provide a value of R. This 'R' value was taken to represent the percentage error between the modelled and actual data.

8.1.2.1 Feedwater temperatures

Appendix B gives details of the methodology used to model the water temperature for Massawa, for which accurate raw data was available.

The polynomial approximation used for seawater temperature at Newhaven, is shown below in Figure 111 with its R^2 value.

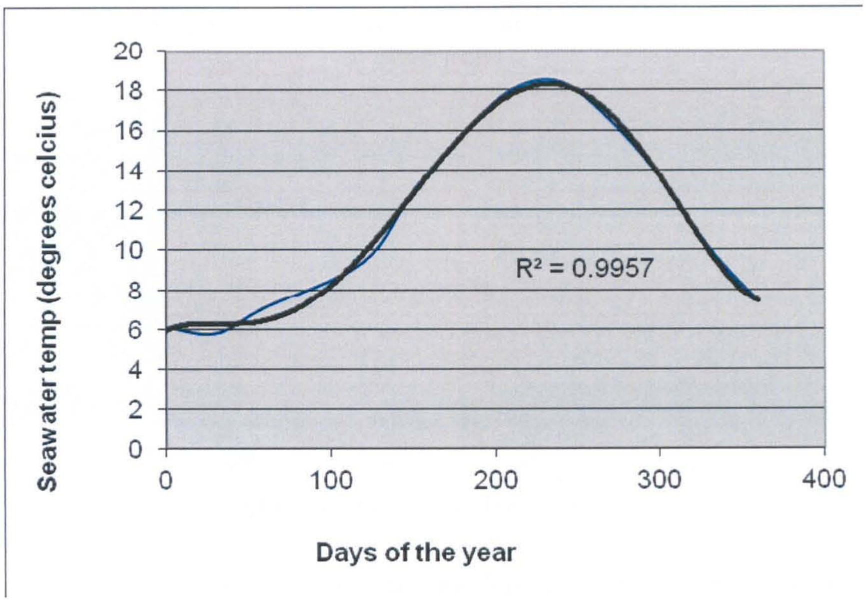

Figure 111: Average feedwater temperature at Newhaven

As can be seen from Figure 111 above, the use of the polynomial with an R^2 value of 0.995 indicates an error 'R' value against the original data of 0.9975,or an error of ±0.25%.

8.1.2.2 Pumping efficiency at varying flowrates

It is clear that to achieve the various flow rates (feedwater delivery, membrane pressurisation, etc), there is a need to vary flowrate. The working assumption for the initial assessment was that the pump and motor system were acting at 80% efficiency, across the full working range.

This constant efficiency was considered unreasonable due to friction, windage losses, design for maximum efficiency at a specific load, etc. The 'DOE Tip sheet 2' [US DoE, 2007], allowed the relationship, shown below in Figure 112, to be derived, between:

- The proportion of maximum flowrate, and
- The corresponding efficiency made up from expected motor Adjustable Speed Drive (ASD[113]) and pump efficiencies at the reduced flowrate.

[113] ASDs save energy by varying the pump's rotational speed to vary the flowrate to achieve optimum power consumption. In centrifugal pumping applications, with no static lift, power requirements vary, as the cube of the pump speed and small decreases in speed or flow rate can significantly reduce energy use. For example, reducing the speed (flow rate) by 20% can lower input power requirements by approximately 50%.

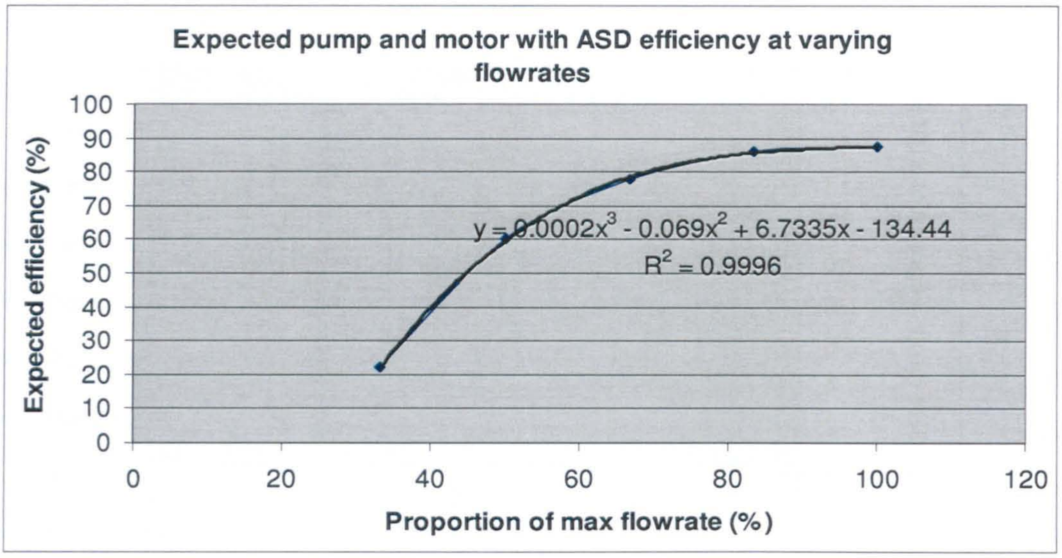

Figure 112: Expected efficiency of pump and motor at various proportions of flowrate

The polynomial equation that corresponds to the curve is included in Figure 112 above. This polynomial was then applied to:

- The No BSR RO plant for the Feedwater and high-pressure pumping power required, and
- The power consumed by each of the BSR plants for:
    - Power to pressurise feed, and
    - Power to move feed/ process water as required.

The use of the polynomial with an R^2 value of 0.9996 shown above in Figure 112 indicates an error 'R' value against the original data of 0.9998, or an error of ±0.02%.

8.1.2.3 RO plant operating profiles

The RO plant operating profiles were derived in two stages of polynomial application:

- Application of the polynomials to the original 14 feedwater temperatures (see example at Appendix B)
- Then using these polynomials to approximate the original 14 feedwater temperatures x14 water production levels x14 power consumed dataset, to provide 3900 discrete polynomials (one for each 0.1 degree rise in feedwater temperature, within the operating range).

The No BSR RO plant original data is shown below in Figure 113 with the polynomial-derived operating profile.

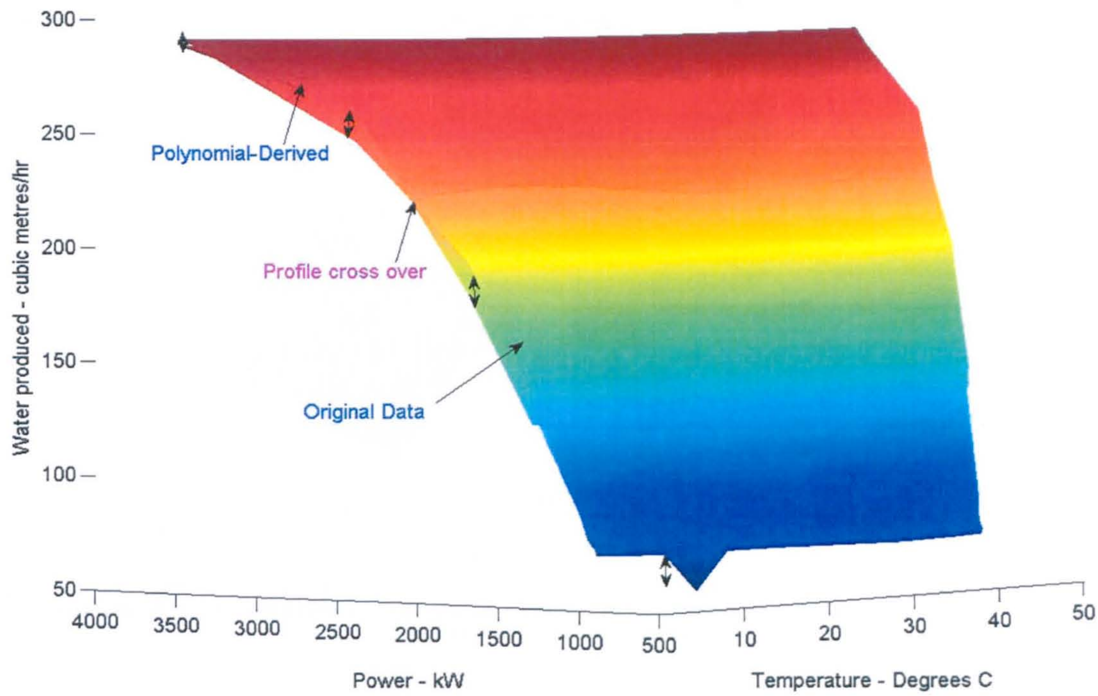

Figure 113: Comparison of No BSR RO plant operating profile derived from original data and the approximated using polynomials

The profiles appear reasonably similar, but it is apparent that there a number of differences, as shown by the double-headed arrows, and that the two profiles cross over. From visual inspection it is taken that there is a maximum error of 5% between the original data and the approximated polynomial surface for any given input values of feedwater temperature and power.

8.1.2.3.2 Pelton Wheel BSR RO Plant

The Pelton Wheel BSR RO Plant operating profile derived from both the original data and the polynomials is shown below in Figure 114.

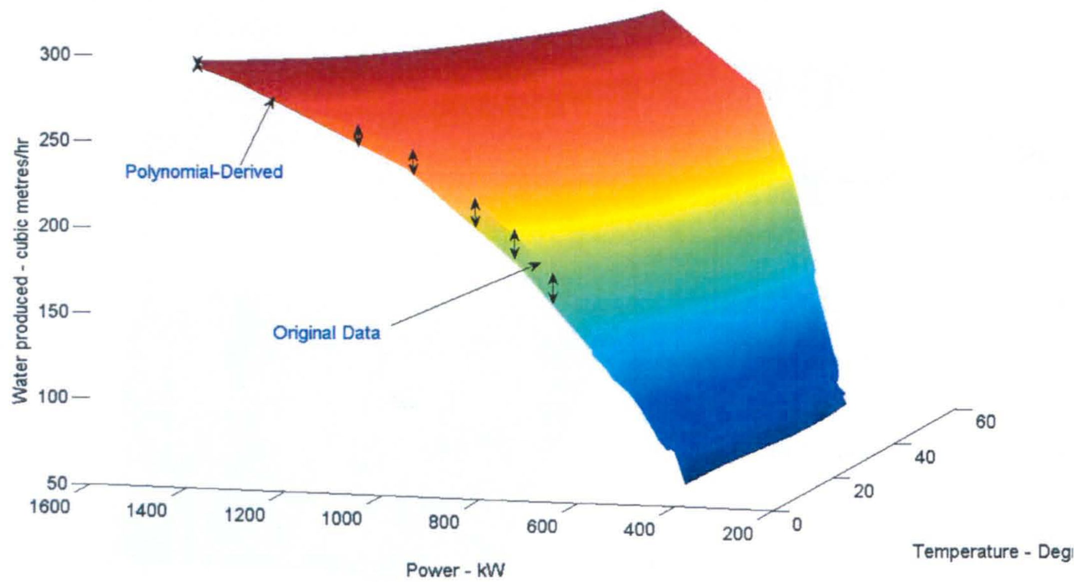

Figure 114: Comparison of Pelton Wheel BSR RO plant operating profile derived from original data and the approximated using polynomials

As can be seen from the double-headed arrows, there is a discernable difference between the two surfaces from around 600kW upwards. Again, based on visual inspection, it is estimated that there is an underestimate of 5% maximum, between the original and polynomial-derived data, for any given input values of feedwater temperature, and power.

8.1.2.3.3 Pressure Exchanger BSR RO Plant

The Pressure Exchanger BSR RO Plant operating profile derived from both the original data and the polynomials is shown below in Figure 115.

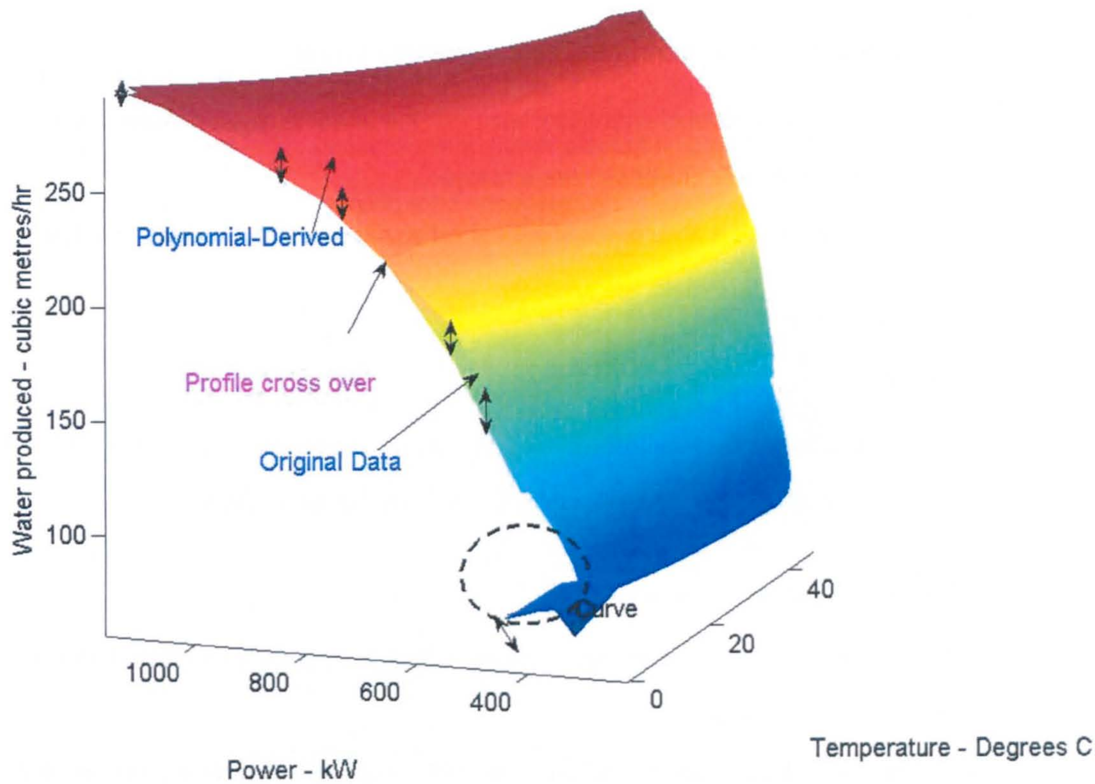

Figure 115: Comparison of Pressure Exchanger BSR RO plant operating profile derived from original data and the approximated using polynomials

The Pressure Exchanger BSR RO plant operating profile was manipulated (to remove the curve at the bottom of the profile, which produced two water production results for a given input power), as explained at Appendix B. Due to this, and the difference between the original data and the polynomial-derived profile, (shown above in Figure 115 which indicates that the two profiles cross-over), it is estimated, by visual inspection, that there is an error of around 10% in the water produced, for any given input values of feedwater temperature and power.

8.1.2.4 Impact of approximations for primary and secondary power

The following section identifies the level of error associated with the use of polynomial approximation for the primary and secondary renewable power sources employed.

For the purposes of this research, it is assumed that the derivation and calculation of hydrogen fuel production, and the estimation of its benefit, are accurate.

8.1.2.4.1 Solar power

The solar power data was developed using HOMER. No data was found on the accuracy of HOMER, but as the derivations were arrived at using average values, it is assumed to be acceptable.

8.1.2.4.2 Tidal current power

The use of polynomials for tidal current power was to derive the power output from SeaGen turbines from the prevailing tidal current stream speed.

Shown below in Figure 116 is the polynomial applied to the tidal current speed at Newhaven, with the associated R^2 value.

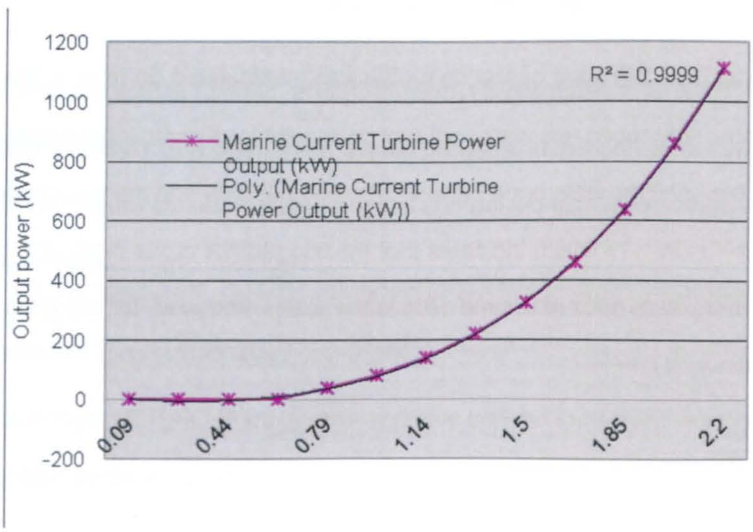

Figure 116: SeaGen Turbine power output at varying tidal current speeds at Newhaven approximated using polynomials

As can be seen from Figure 116 above, the use of the polynomial with an R^2 value of 0.999 indicates an error against the original data of 0.9995, or an error of ±0.05% associated with the derivation of tidal current power from the SeaGen turbine.

8.1.2.4.3 Wind power

Polynomials were employed to derive the wind power production profile (Figure 117) of the scaled-up Fuhrlander 250 wind turbine, at varying wind speeds, with the associated R^2 value.

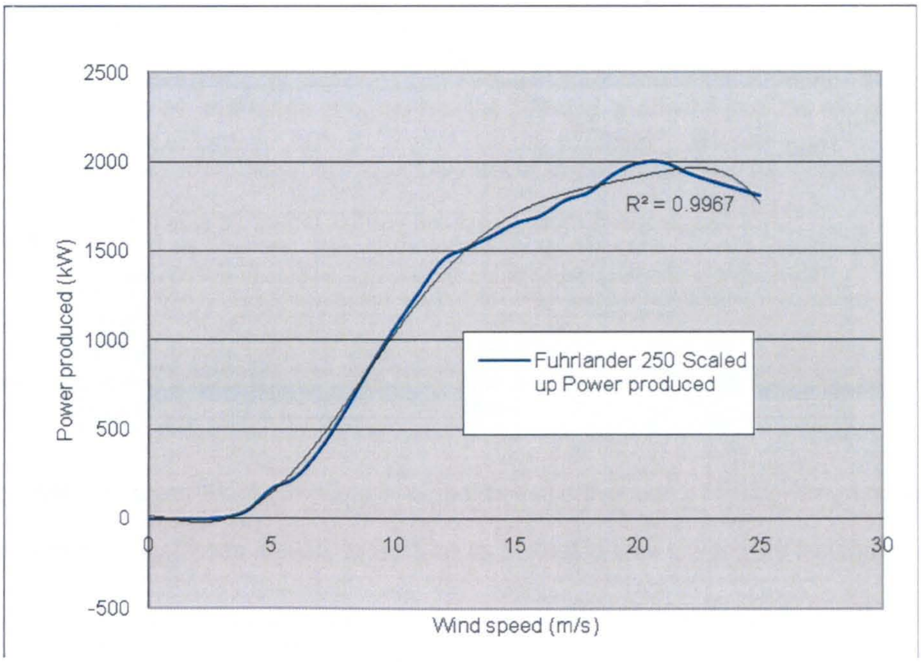

Figure 117: Scaled-up Fuhrlander 250 power output at varying wind speeds, approximated using polynomials

As can be seen from Figure 117above, the use of the polynomial with an R^2 value of 0.996 indicates an error 'R' value against the original data of 0.998, or an error of ±0.2% associated with the derivation of wind power from the scaled-up Fuhrlander wind turbine.

8.1.2.4.4 Wave power

Polynomials were employed to derive the wave power production profile (Figure 118) of the Wave Dragon device at varying wave heights, with the associated R^2 value.

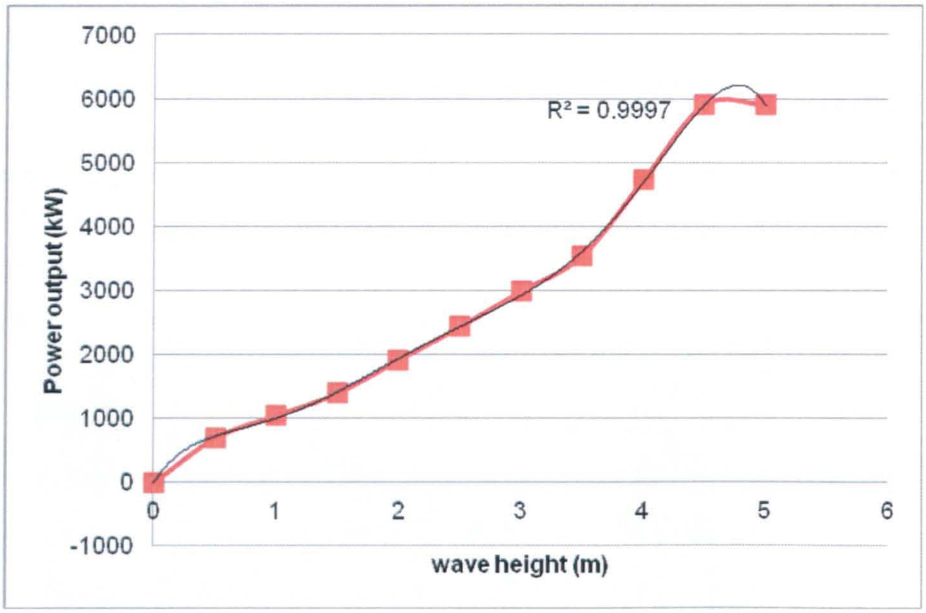

Figure 118: Wave Dragon power output at wave period of 7 seconds with varying wind speeds approximated using polynomials

As can be seen from Figure 118 above, the use of the polynomial with an R^2 value of 0.999 indicates an error 'R' value against the original data of 0.9995, or an error of ±0.05% associated with the derivation of wave power from the Wave Dragon device.

8.1.2.4.5 Use of hydrogen fuel

The use of hydrogen fuel was modelled without the use of polynomials and is taken to be accurate at a constant 22% round-trip efficiency at all loads.

8.1.2.5 Conclusion

Of the errors identified above, there were two that had a large impact on the results:

- Accuracy of RO plant profiles, and
- Fitting of polynomials to RO plant profiles.

The other errors identified above are shown below in Table 64, and are considered to be relatively small.

Table 64: Minor errors associated with polynomial approximations

Variable	Massawa (±%)	Newhaven (±%)
Feedwater temperature	0	0.25
Pumping efficiency	0.02	0.02
Tidal current power	-	0.05
Wind power	0.2	0.2
Wave power	0.05	0.05

As such, it is considered that the errors due to modelling approximations are generally small, but two errors associated the approximation of RO plant profiles, shown below in Table 65, are more significant.

Table 65: More significant errors associated with modelling approximations

RO plant	$E_{real\ world\ RO\ plant\ data}$		$E_{RO\ plant\ operating\ profile}$	
	Massawa (%)	Newhaven (%)	Minimum (%)	Maximum (%)
No BSR	0	0	-5	+5
Pelton Wheel BSR	-10	-10	+5	+5
Pressure Exchanger BSR	-5	+10	-10	+10

As shown below in Table 66, this range of errors has the potential to affect five of the results which are closest to financial viability when externalities are applied at Massawa, but has no effect on the results at Newhaven, as shown in Table 67 below as they are too far from financial viability.

Table 66: Estimated impact of polynomial approximations at Massawa

Stage	Type of RO plant	Type of Secondary Power	Hydrogen Fuel used?	Cost ratio against conventional energy	Cost ratio against conventional with externalities	Estimated effect of polynomial approximations on financial viability.
1	No BSR	None	No	1.46	1.01	May make scenario with externalities viable.
2	Pelton Wheel	None	No	1.694	1.392	None
	Pressure Exchanger	None	No	1.643	1.373	None
3	No BSR	wind	No	1.227	0.85	None
	Pelton Wheel	wind	No	1.353	1.112	None
	Pressure Exchanger	wind	No	1.423	1.19	None
	No BSR	wave	No	1.289	0.894	None
	Pelton Wheel	wave	No	1.286	1.057	None
	Pressure Exchanger	wave	No	1.273	1.064	None
4	No BSR	None	Yes	1.47	1.02	May make scenario with externalities viable.
	Pelton Wheel	None	Yes	1.434	1.178	None
	Pressure Exchanger	None	Yes	1.402	1.172	None
	No BSR	wind	Yes	1.298	0.9	None
	Pelton Wheel	wind	Yes	1.23	1.012	None
	Pressure Exchanger	wind	Yes	1.212	1.013	May make scenario with externalities viable.
	No BSR	wave	Yes	1.261	0.8746	None
	Pelton Wheel	wave	Yes	1.189	0.9773	May make scenario with externalities unviable.
	Pressure Exchanger	wave	Yes	1.226	1.024	May make scenario with externalities viable.

Table 67: Estimated impact of polynomial approximations at Newhaven

Stage	Type of RO plant	Type of Secondary Power	Hydrogen Fuel used?	Cost ratio against conventional energy	Cost ratio against conventional with externalities	Estimated effect of polynomial approximations on financial viability.
1	No BSR	None	No	2.969	2.848	None
2	Pelton Wheel	None	No	2.525	2.479	None
	Pressure Exchanger	None	No	2.469	2.426	None
3	No BSR	wind	No	1.527	1.465	None
	Pelton Wheel	wind	No	1.38	1.355	None
	Pressure Exchanger	wind	No	1.358	1.334	None
	No BSR	wave	No	1.443	1.384	None
	Pelton Wheel	wave	No	1.196	1.174	None
	Pressure Exchanger	wave	No	1.188	1.168	None
4	No BSR	None	Yes	3.113	2.986	None
	Pelton Wheel	None	Yes	2.471	2.425	None
	Pressure Exchanger	None	Yes	2.368	2.327	None
	No BSR	wave	Yes	1.57	1.507	None
	Pelton Wheel	wave	Yes	1.209	1.187	None
	Pressure Exchanger	wave	Yes	1.204	1.184	None
	No BSR	wind	Yes	1.504	1.443	None
	Pelton Wheel	wind	Yes	1.265	1.242	None
	Pressure Exchanger	wind	Yes	1.198	1.177	None

It is concluded overall, that the more significant modelling errors, which have been approximately assessed as part of this research are likely to have some impact on the results, but they would need to be assessed more accurately to properly quantify the impact on the results.

8.2 Variables that are most likely to impact on viability of scenarios

It is considered that six variables have potential for significant impact on the viability of the scenarios modelled. These are:

- Diesel Fuel costs
- Solar power
- Wind Speed
- Wave Height
- Feedwater temperature, and
- The impact of intermittent operation on the RO plant.

These variables have a strong influence on the financial viability findings of this research.

8.2.1 Diesel Generator costs

As can be seen from the results thus far, the financial viability of the Massawa scenarios is heavily reliant on the comparison with the life cycle costs of the use of diesel generators, and in particular, the costs of the diesel fuel itself.

The diesel fuel cost over the past 20 years in Eritrea have been particularly erratic [Ebert et al, 2009], as shown below in Figure 119.

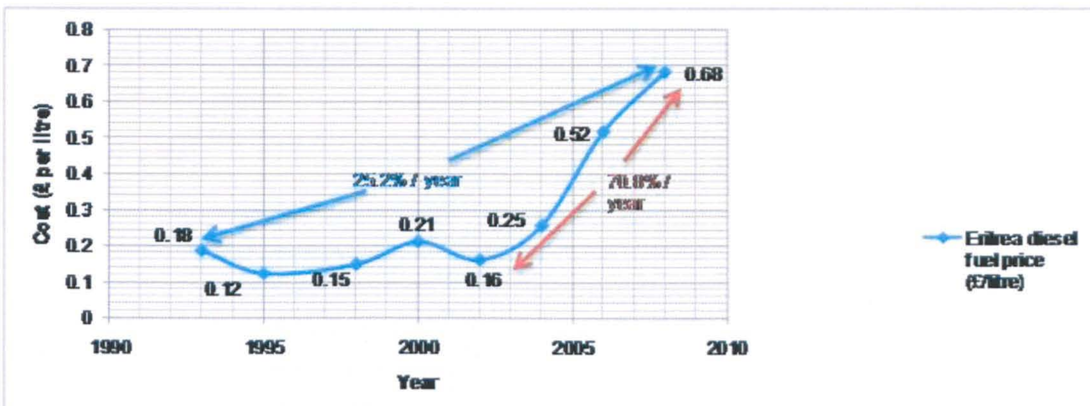

Figure 119: Historic diesel fuel price in Eritrea from 1993 – 2008

As can be seen from Figure 119 above, from 1993 – 2008, the cost difference of diesel represents an annual increase of 25.2% per year. If the sample period is then taken as 2002 – 2008, the cost difference almost triples, to an increase of 70.8% per year.

For the purposes of this research, it was considered more reasonable to apply a straight line graph to interpolate the diesel fuel cost over the life of the installation, as shown below in Figure 120 as the 'Trend Line'---.

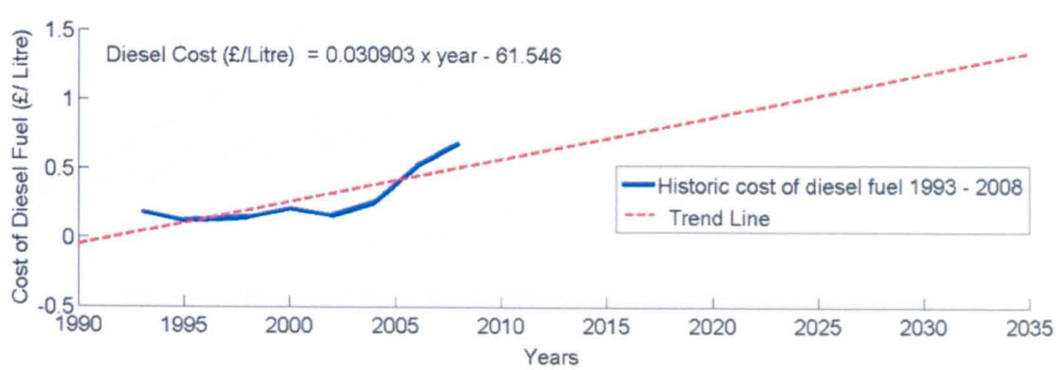

Figure 120: Diesel fuel price in Eritrea over life of RO plant installation

This trend resulting in fuel price rises as shown in Table 68 below, based on the assumption that the RO plant installation is constructed in 2012. This equates to an annual rise of just below 5%, and in 2036 is still below the diesel fuel price in the UK [AA, 2011].

Table 68: Diesel fuel costs over life of RO plant installation.

Year	Cost of diesel fuel (£/Litre)
2012	0.6248
2013	0.6557
2014	0.6866
2015	0.7175
2016	0.7484
2017	0.7793
2018	0.8102
2019	0.8411
2020	0.872
2021	0.9029
2022	0.9338
2023	0.9647
2024	0.9956
2025	1.0265
2026	1.0574
2027	1.0883
2028	1.1192
2029	1.1501
2030	1.181
2031	1.2119
2032	1.2428
2033	1.2737
2034	1.3046
2035	1.3355
2036	1.3664

These diesel fuel prices result in the generator size to diesel fuel costs shown below in Figure 121.

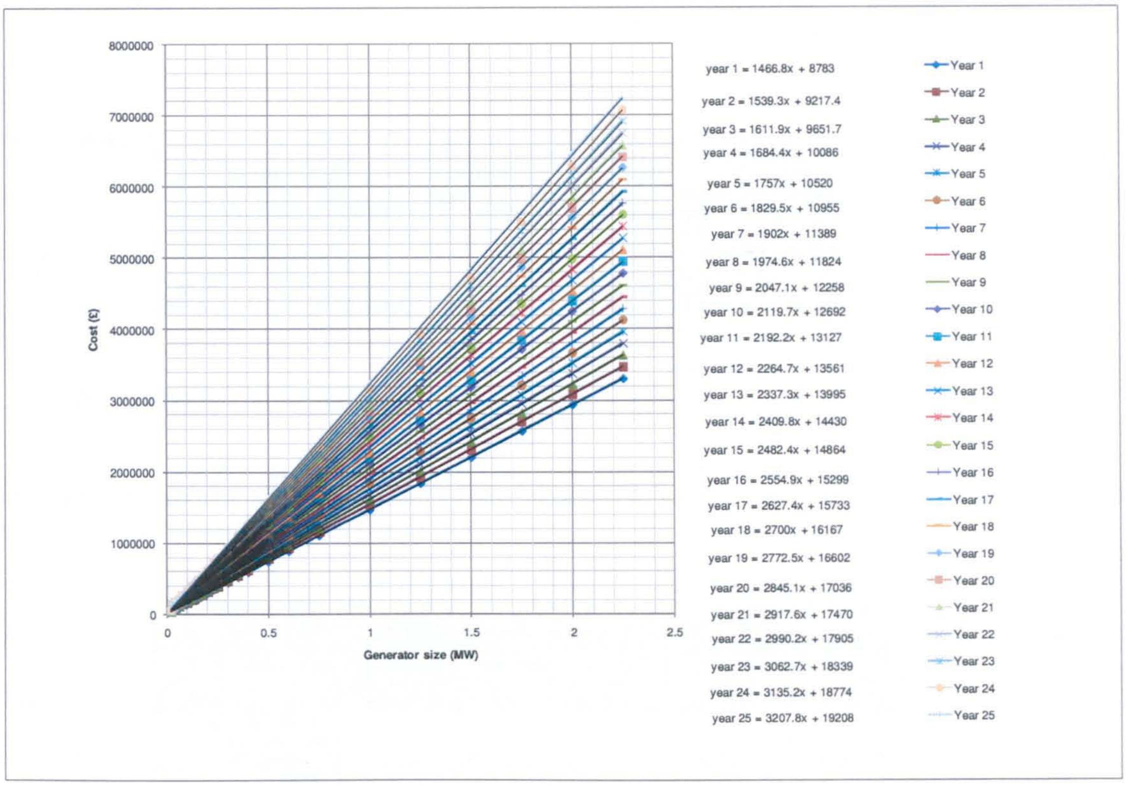

Figure 121: Varying diesel fuel price over life of RO plant installation

The diesel fuel costs are shown below in Figure 122 for their particular reverse osmosis plant scenarios, taking the increase in diesel price into account.

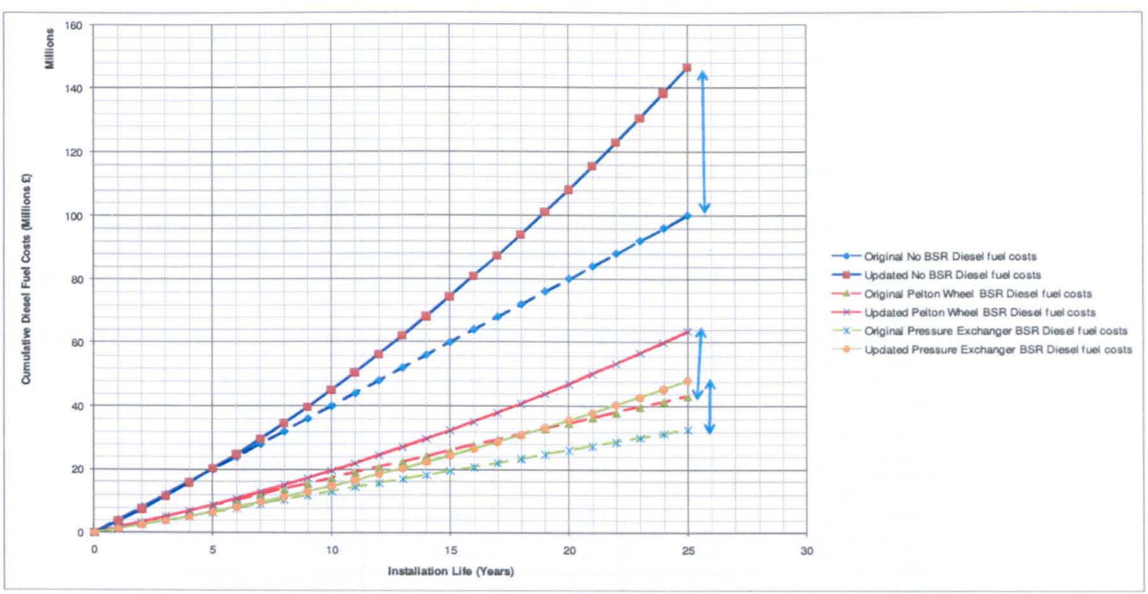

Figure 122: The cost of diesel fuel for different RO Plant scenarios, over 25 years

As can be seen from the double-headed arrows in Figure 122 above, the greatest difference in cost occurs with the No BSR scenario, due to the higher diesel fuel consumption for this scenario.

The results of increasing the diesel fuel costs for each of the conventionally-powered scenarios, is shown below in Table 69.

Table 69: Percentage change in overall cost of RO plant scenarios due to increasing diesel fuel costs.

	Constant fuel without externalities ($£x10^7$)	Previous with externalities ($£x10^7$)	Updated without externalities ($£x10^7$)	Updated with externalities ($£x10^7$)	Percentage increase in cost without externalities due to increasing diesel costs (%)	Percentage increase in cost with externalities due to increasing diesel costs (%)
No BSR	23.16	33.40	27.83	38.06	20.1	14.0
Pelton Wheel BSR	20.48	24.92	22.52	26.96	9.9	8.17
Pressure Exchanger BSR	17.11	20.47	18.66	22.02	9.0	7.6

Table 70 below shows the estimated impact of increasing diesel fuel costs on the financial viability of the scenarios.

Table 70: Estimated impact of increasing diesel fuel costs at Massawa

Stage	Type of RO plant	Type of Secondary Power	Hydrogen Fuel used?	Cost ratio against conventional energy	Cost ratio against conventional with externalities	Estimated effect of increasing diesel fuel costs.
1	No BSR	None	No	1.46	1.01	Would make scenario with externalities financially viable.
2	Pelton Wheel	None	No	1.694	1.392	None
	Pressure Exchanger	None	No	1.643	1.373	None
3	No BSR	wind	No	1.227	0.85	Would be within 2.5% of financial viability without externalities.
	Pelton Wheel	wind	No	1.353	1.112	None
	Pressure Exchanger	wind	No	1.423	1.19	None
	No BSR	wave	No	1.289	0.894	Would be within 9% of financial viability without externalities.
	Pelton Wheel	wave	No	1.286	1.057	Would make scenario with externalities financially viable.
	Pressure Exchanger	wave	No	1.273	1.064	Would make scenario with externalities financially viable.
	No BSR	None	Yes	1.47	1.02	Would make scenario with externalities financially viable.
	Pelton Wheel	None	Yes	1.434	1.178	None
	Pressure Exchanger	None	Yes	1.402	1.172	None
4	No BSR	wave	Yes	1.298	0.9	None
	Pelton Wheel	wave	Yes	1.23	1.012	Would make scenario with externalities financially viable.
	Pressure Exchanger	wave	Yes	1.212	1.013	Would make scenario with externalities financially viable.
	No BSR	wind	Yes	1.261	0.8746	None
	Pelton Wheel	wind	Yes	1.189	0.9773	None
	Pressure Exchanger	wind	Yes	1.226	1.024	Would make scenario with externalities financially viable.

As can be seen from Table 70 above, a very conservative increase in the diesel fuel price results in:

- A large proportion of scenarios (7 out of 15 that were not already financially viable with externalities applied) becoming financially viable, and

- The No BSR scenarios, with wind and wave, closing to 2.5% and 9% of financial viability without externalities, respectively.

The financial viability results presented in this thesis for Massawa are highly susceptible to prevailing diesel fuel costs. It is considered highly likely that increases in diesel fuel costs, associated with reduced supplies over the next 25 years, will result in diesel fuel costs increasing significantly more than modelled. This will improve the prospects for financial viability of the Massawa RO plant scenarios.

8.2.2 Reliance on Solar power for viability

As can be seen from the results thus far, the solar-powered scenarios have been quite successful financially, when compared to the conventional scenarios. This is not particularly surprising considering the quantity of sunlight in Eritrea, and the externalities associated with the use of diesel fuel, but the solar array considered for this research assumes that 10% of the available radiation at any time when the sun is shining is captured and converted to usable electrical power. Although 10% is the lowest efficiency associated with mono-crystalline silicon, (see Appendix B), the model may have given the solar power delivered at Massawa more credit that it is due, because there are other factors that affect the performance of PV panels that have not been considered.

In reality, the output of a solar cell depends upon several factors beyond those modelled:

- The properties of the semi-conductor material
- The intensity of solar irradiance
- The cell temperature, and
- The nature of the external loads the cell supplies.

The combination of these factors gives rise to the characteristic operating curves, of generated current against the output voltage for the solar cell (known as I-V curves). The I-V curve for the Sharp 235 watt multi-purpose module used as the basis for the modelling, is shown below[114] in Figure 123.

[114] Available at http://www.solarelectricsupply.com/Solar_Panels/Sharp/images/IV-Curves-235.gif [Last viewed on 7 August 2011].

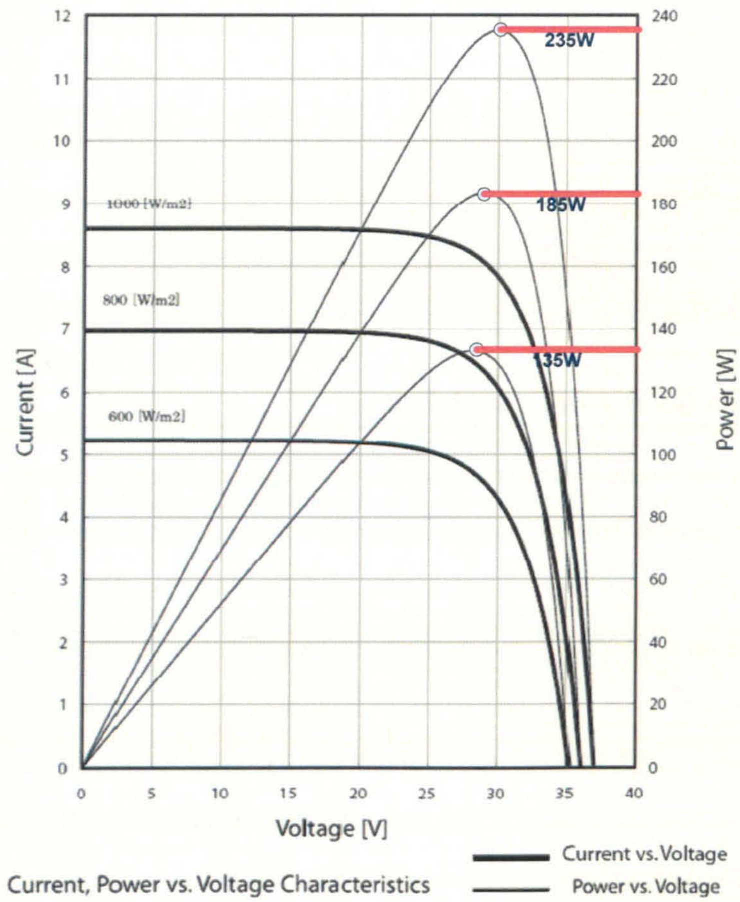

Figure 123: The characteristic I-V operating curve for the Sharp NU-235F1 solar module

The Power vs. Voltage curve (the thin-lined curves) in Figure 123 above, indicates the approximate maximum power delivered at each corresponding level of irradiance.

8.2.2.1 Impact of ambient temperature

There is also the impact of ambient temperature on the efficiency of the power output from the panel, which in general means that a crystalline silicon PV module's efficiency will be reduced by about 0.5 percent for every degree C increase in temperature. PV modules are usually rated at module temperatures of 25°C (77°F). In addition, they normally operate at about 20°C above the ambient air temperature, which further reduces the PV module's efficiency. For Massawa, with its typically high ambient air temperature of 45°C but which can reach 50°C, this would mean a 22.5% reduction[115] in power output (Butay and Miller).

[115] Panel temperature would be 45°C above normal test rated temperature of 25°C giving a reduction in power output of 22.5%, due to the combination of:

- Ambient air temperature being 25°C above normal test rated temperature of 25°C, giving a (25 x 0.5 =) 12.5% reduction in power output and
- Panel working temperature being a further 20°C above ambient temperature giving an additional (20 x 0.5) = 10% reduction in power output.

The effect of the solar power available for the panel, and the impact of 50°C ambient temperature, is shown below in Figure 124 in relation to the modelled power output.

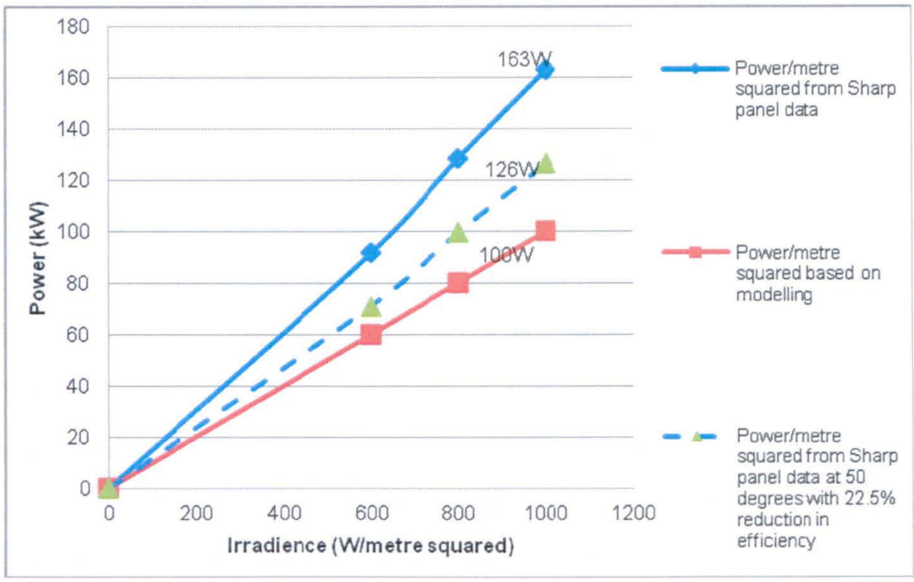

Figure 124: Comparison of modelled solar power output against rated data, with and without ambient temperature effect.

As can be seen from Figure 124 above, the maximum possible power output is around 60% greater than the value modelled, but once the effects of high ambient temperature are applied, this margin reduces to around 26%. This, though, is without taking into account other potential variables, which could reduce the power output such as:

- The 'clearness factor' applied within the renewable energy modelling software (HOMER)
- Potential for overcast days
- Cleanliness of the panel surface
- Ability of the RO plant to operate at the maximum power output level for the prevailing irradiance.

So, it is considered that in practice, the modelled solar power scenarios, with their relatively simplistic 10% rating, are probably close to correct, and the financial viability results are not significantly affected, but the following will need to be investigated further if the modelled results are to be accurate:

- The local 'clearness factor' and potential for overcast days at Massawa, and
- The practicalities of operating and maintaining the solar scenarios.

8.2.3 **Reliance on wind power for viability**

Wind power (as an established, and relatively cheap source of power) has been identified within the financially-viable scenarios at Massawa based on the wind speed profile obtained from the renewable energy modelling software (HOMER).

8.2.3.1 Scrutiny of the wind profiles for each site

The Weilbull distribution was employed within HOMER, to derive wind speeds for each hour of the year, based on monthly averages. The 'Shape Factor' is a feature of the Weilbull distribution which approximates the level of erraticness of the wind speed, over a given time period, and for the purposes of this research was taken as '2'. In reality, according to the 'wind evaluation' website [Wind Site Evaluation], it ranges in value from about 1.5 to 3.0, and hence the viability results are susceptible to variation, based on this range of the erraticness parameter.

To investigate the potential impact of different levels of wind speed 'erraticness' for Newhaven and Massawa, the following 'k' value parameters were remodelled within HOMER.

- 1.5
- 2
- 2.5, and
- 3.

Shown below in Table 71, are the percentages of annual wind speed distribution that are below the 'cut in' speed of 3m/s, which will not generate power for each of the 'k' values.

Table 71: Proportion of annual windspeeds below 'cut in' speed at each site, at different 'k' values.

'k' Value	Portion of annual wind speed below 'cut in' speed (%)		Difference from k=2 (%)	
	Massawa	Newhaven	Massawa	Newhaven
1.5	33.3	26.7	9.7	8.8
2.0	23.6	17.9	0	0
2.5	17.5	12.2	-6.1	-4.3
3.0	12.7	8.5	-10.9	-9.4

As can be seen from Table 71 above, the portion of the year that contains wind speeds below the threshold to generate power, varies between around 10 and 9% from the k=2 value, for Massawa and Newhaven, respectively. It is evident that any changes to the 'k' value within the scenarios, would have an appreciable impact on the results.

Figure 125 and Figure 126 below, show the power produced over one year, based on the various k values, from the scaled-up Fuhrlander 250 wind turbine at Massawa and Newhaven, respectively.

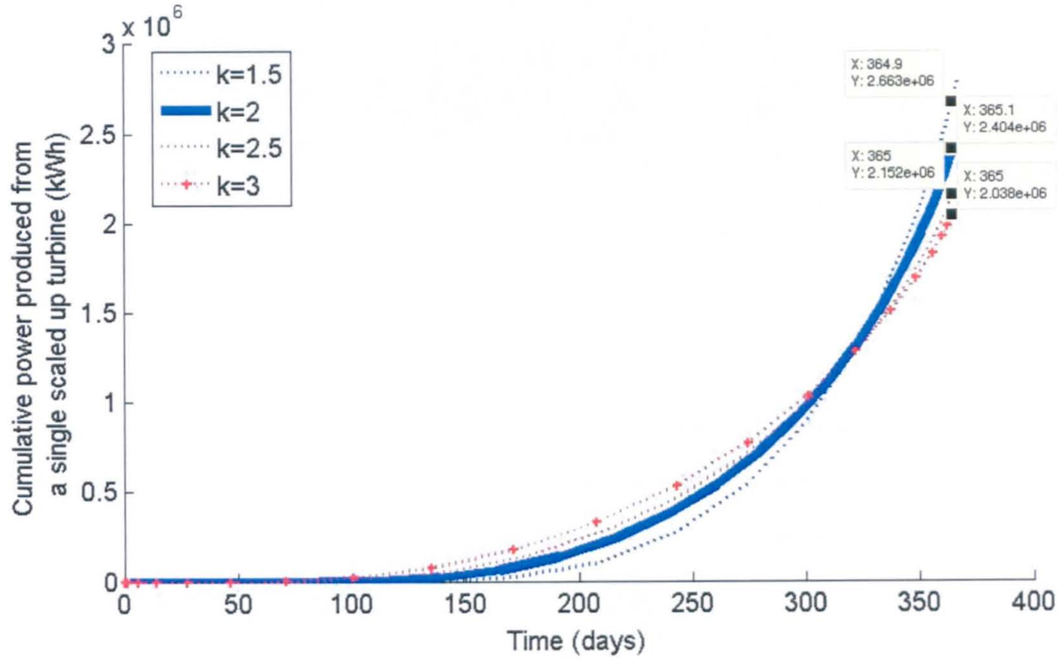

Figure 125: Comparison of power produced by scaled up Fuhrlander 250, for various k values, at Massawa

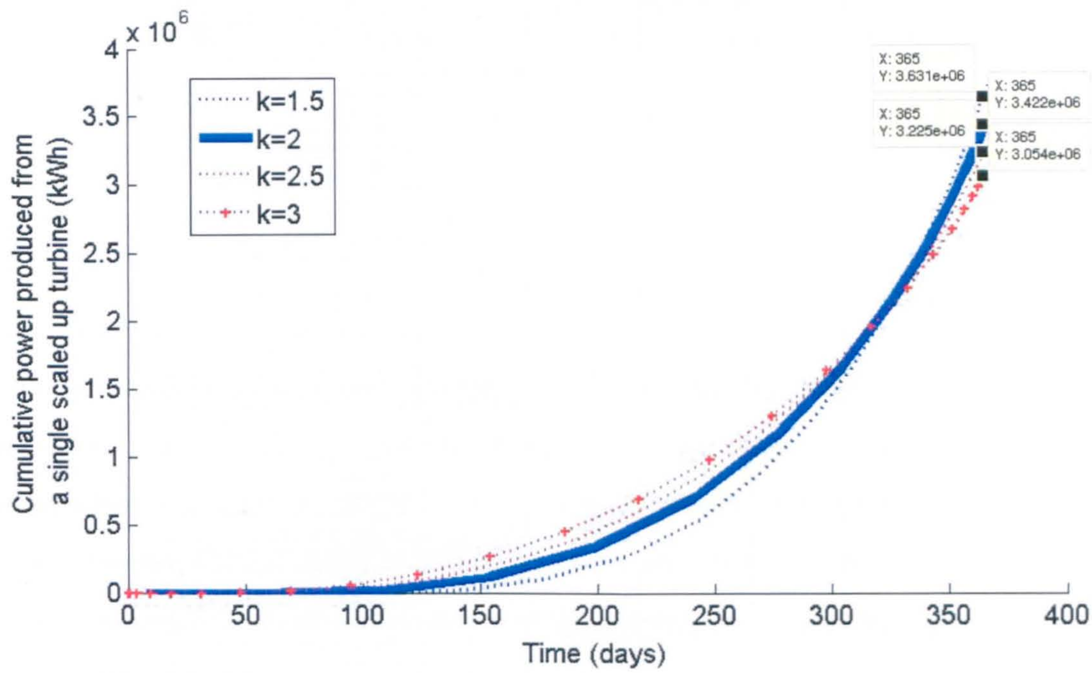

Figure 126: Comparison of power produced by scaled up Fuhrlander 250, for various k values, at Newhaven

Table 72 below gives a comparison of the power produced over the course of the year, for various k values. The values for k = 2 (used in this research) can be seen in context.

Table 72: Comparison of wind power produced in relation to k=2

Weilbull (k) value	Newhaven		Massawa	
	Power produced during year (kWh)	Percentage increase/ decrease on k = 2 power production	Power produced during year (kWh)	Percentage increase/ decrease on k = 2 power production
1.5	$3.6x10^6$	5.9	$2.7\ x10^6$	12.5
2	**$3.4\ x10^6$**	**0**	**$2.4\ x10^6$**	**0**
2.5	$3.2\ x10^6$	-5.9	$2.2\ x10^6$	-10.7
3	$3.1\ x10^6$	-11.8	$2.0\ x10^6$	-15.4

8.2.3.2 Conclusion

Table 73 and Table 74 below summarise the conclusions from the scrutiny of wind power k-value variability for Massawa and Newhaven, respectively. The conclusions are based on:

- The maximum potential change in energy produced
- The extent of financial viability/ shortfall to achieve financial viability, and
- The proportion of wind power within the scenario.

Table 73: Conclusions for impact of a k value change (from '2' used in the modelling) for Massawa wind scenarios

RO Plant Type	Hydrogen fuel used?	Cost ratio against conventional power	Cost ratio against conventional power with externalities	Impact of k values
No BSR	No	1.227	0.85	It is unlikely that the use of a different k value would make this scenario viable without externalities being applied, or be made unviable with externalities applied as: • The amount of wind power available could only increase around 12.5% • This scenario only uses 36% wind power giving a maximum change of around 4.5%.
Pelton Wheel	No	1.353	1.112	It is unlikely that a change of k value resulting in 12.5% more power being produced would make this scenario financially viable with externalities applied as: • It is more than 11% away from financial viability, and • The scenario is made up of around 80% wind power giving a 9.6% maximum change.
Pressure Exchanger	No	1.423	1.19	It is unlikely that a change of k value resulting in 12.5% more power being produced would make this scenario financially viable, even with externalities applied as: • It is 19% away from financial viability, and; • The scenario is made up of around 80% wind power giving a maximum of less than 10% change.
No BSR	Yes	1.261	0.8746	It is unlikely that a different k value would make this scenario unviable when externalities are applied, as: • The maximum reasonable decrease in power is around 15% • It is over 12.5% within financial viability, and; • This scenario uses around 70% wind power giving a maximum change of 10.5%.
Pelton Wheel	Yes	1.189	0.9773	It is likely that the use of different k value decreasing the power available by 15% would make this scenario unviable with externalities applied, as: • It is less than 2.3% within financial viability, and • The scenario is heavily reliant on wind which makes up over 70% giving a maximum change of 10.5%.
Pressure Exchanger	Yes	1.226	1.024	It is possible that a different k value increasing the power available by 15% would make this scenario viable with externalities applied, as: • It is less than 2.5% away from financial viability, but • The scenario is heavily reliant on wind which makes up around 70% giving a maximum change of 10.5%.

Table 74: Conclusions for impact of a k value change (from '2' used in the modelling) for Newhaven wind scenarios

RO Plant Type	Hydrogen fuel used?	Cost ratio against conventional power	Cost ratio against conventional power with externalities	Impact of k values
No BSR	No	1.527	1.465	It is unlikely that use of a different k value increasing the power available by 5.9% would make this scenario financially viable, as: • The scenario is almost 47% outside the viability zone, and • This scenario uses around 60% wind power giving a maximum change of around 3.5%.
Pelton Wheel	No	1.38	1.355	It is unlikely that use of a different k value increasing the power available by 5.9% would make this scenario financially viable, as: • The scenario is more than 35% outside the viability zone, and • This scenario uses around 70% wind power giving a maximum change of just over 4%.
Pressure Exchanger	No	1.358	1.334	It is unlikely that use of a different k value increasing the power available by 7.9% would make this scenario financially viable, as: • The scenario is more than 33% outside the viability zone, and • This scenario uses around 75% wind power giving a maximum change of 4.5%.
No BSR	Yes	1.504	1.443	It is unlikely that use of a different k value increasing the power available by 5.9%would make this scenario financially viable, as: • The scenario is more than 44% outside the viability zone, and • This scenario uses around 60% wind power giving a maximum change of around 3.5%.
Pelton Wheel	Yes	1.265	1.242	It is unlikely that use of a different k value increasing the power available by 5.9% would make this scenario financially viable, as: • The scenario is more than 24% outside the viability zone, and • This scenario uses around 50% wind power giving a maximum change of less than 3%.
Pressure Exchanger	Yes	1.198	1.177	It is unlikely that use of a different k value increasing the power available by 7.9% would make this scenario financially viable, as: • The scenario is nearly 18% outside the viability zone, and • This scenario uses around 70% wind power giving a maximum change of just over 4%.

Overall, it is expected that varying 'k' values will have a limited impact on the financial viability of the scenarios at Massawa, (particularly in making scenarios financially viable when externalities are applied), and no impact at all at Newhaven. This said, there is the potential for increases and decreases in wind power, to have a disproportionate effect on the water produced, and therefore viability, by either:

- Providing additional power at a time when the primary source does not function, or
- Providing additional power at a time when the primary source is already providing the maximum amount of water.

As such, it is considered that a project of this type would benefit from having on-site wind speed data, and this is worthy of further investigation.

8.2.3.3 General variability of wind

There is also a potential concern that 50,000 people may rely on potentially-erratic wind supplies for their drinking water, and it may be that in practice:

- There is a ceiling (say 20% – 40%) placed on the percentage of installed power that is wind-based, or
- The installed solar power (and hydrogen fuel) must be such as to deliver a set amount of water (say 70%) unassisted by wind.

What design methodology is best, and what limits to apply, are also considered to be worthy of further investigation, to ensure that in practice the water supply is not unduly threatened by the erraticness of the prevailing wind.

8.2.4 Reliance on wave power for viability

A simple scale-up model was generated where wave power as an effective source of power was identified as financially viable for a number of scenarios, based on the profile obtained from ARGOSS, (detailed in Appendix B). The most frequently-occurring wave height for each month was applied.
In reality, the wave spectrum is a complex fluid landscape, made up of waves on top of waves.
The wave height value that is normally employed to rationalise this complexity is the *significant wave height*. Significant wave height (H_s)[116] is defined as the average height of the highest one-third waves in a wave spectrum and, is shown below in Figure 127 in relation to the probability of waves of all heights.
This relates to the fact that the wave height estimated by a trained observer will only be a fraction of the wave heights occurring at a particular time.

8.2.4.1 Scrutiny of the wave profiles for each site

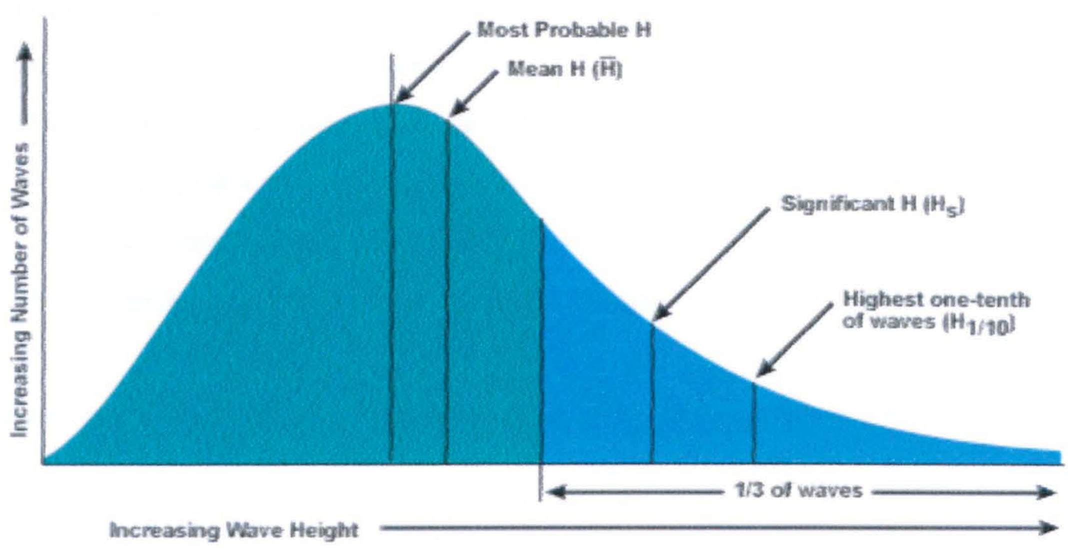

Figure 127: Wave height distribution including significant wave height.

[116] The significant wave height was intended to mathematically express the height estimated by a "trained observer".

The significant wave height is depicted in Figure 127. It can be seen (since the x-axis shows increasing wave height) that the most probable wave height offers a lower value than the significant wave height. Shown below in Figure 128 and Figure 129 are the monthly wave height distribution curves for Massawa and Newhaven, respectively, indicating approximate wave height ranges associated with 'most probable' and 'significant wave heights'.

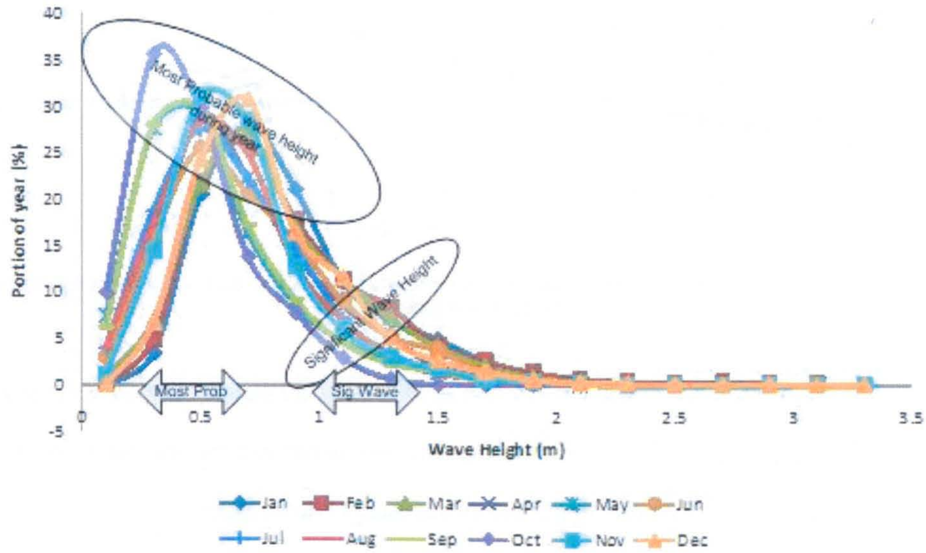

Figure 128: Wave height distribution at Massawa.

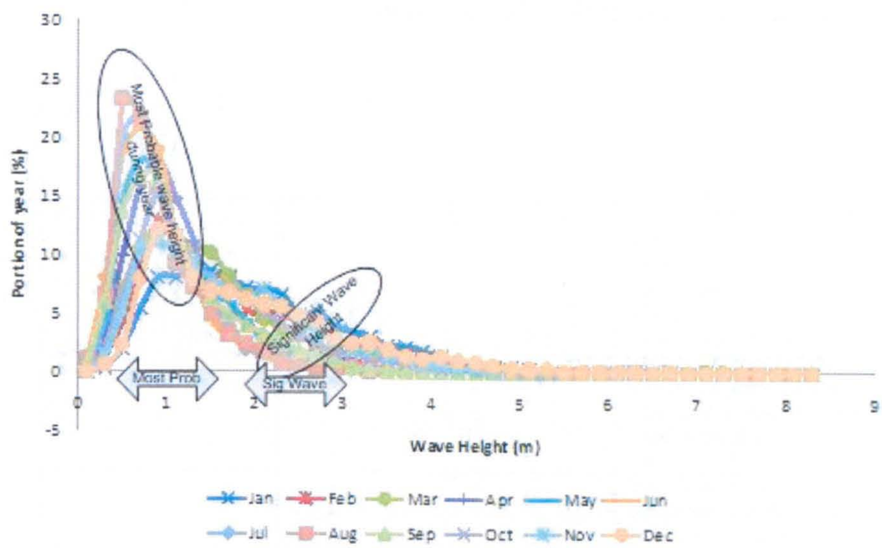

Figure 129: Wave height distribution at Newhaven.

As can be seen from Figure 128 and Figure 129 above, using the most probable wave height gives a much lower monthly wave height than if the significant wave height were used.

It would appear that the modelling has underestimated the wave height, and the impact of this underestimation is shown below in Figure 130, which illustrates the difference in power expected using approximate averages at each site.

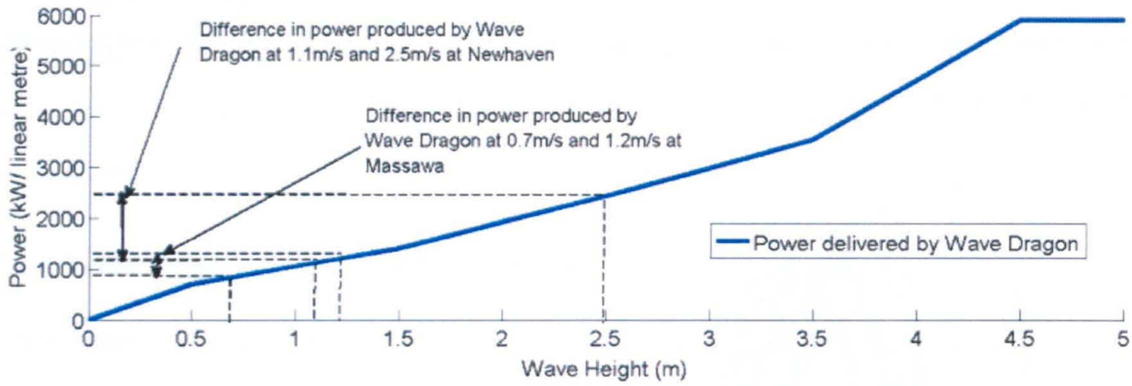

Figure 130: Difference in average power produced between 'most probable' and 'significant wave heights', at Massawa and Newhaven.

It can be seen that the effect on power production at Massawa is relatively limited with around an additional 50% wave power due to the use of significant wave height, but the improvement at Newhaven is more significant, almost doubling due to the use of significant wave height.

As such, it is considered that the use of significant wave heights would have the impacts described in Table 75 and Table 76 for Massawa and Newhaven, respectively. The scenario's highlighted in yellow are likely to be impacted by the use of significant wave height.

Table 75: Impact of using significant wave height at Massawa

Type of RO plant	Solar/ Wave Power (MW)	Hydrogen Fuel used?	Ratio of renewable scenario cost against conventional	Ratio against conventional with externalities	Impact of using significant wave height
No BSR	15.82/ 22.14	No	1.289	0.894	Potential to become financially viable without externalities, as: • 50% more wave power could be available • This scenario uses more than 60% wave power, and • Has less than 30% shortfall to viability.
Pelton Wheel	4/ 12.53	No	1.286	1.057	Very likely to become financially viable without externalities as: • 50% more wave power could be available • This scenario uses around 80% wave power, and • Has less than 30% shortfall to viability. • This scenario will almost certainly become viable once externalities are applied, due to shortfall of only 6%.
Pressure Exchanger	2.98/ 12.15	No	1.273	1.064	Very likely to become financially viable without externalities, as: • 50% more wave power could be available • This scenario uses around 80% wave power, and • Has less than 30% shortfall to viability. • This scenario will almost certainly become viable once externalities are applied, due to shortfall of only 6%.
No BSR	9.69/ 19.73	Yes	1.298	0.9	Potential to become financially viable without externalities, as: • 50% more wave power could be available • This scenario uses more than 65%% wave power, and • Has just over 30% shortfall to viability.
Pelton Wheel	3.41/ 10.68	Yes	1.23	1.012	Very likely to become financially viable without externalities, as: • 50% more wave power could be available • This scenario uses around 75% wave power, and • Has a 23% shortfall to viability. • This scenario will almost certainly become viable once externalities are applied due to shortfall of around 1%.
Pressure Exchanger	2.67/ 8.14	Yes	1.212	1.013	Very likely to become financially viable without externalities, as: • 50% more wave power could be available • This scenario uses around 75% wave power, and • Has less than 22% shortfall to viability. • This scenario will almost certainly become viable once externalities are applied, due to shortfall of around 1%.

Table 76: Impact of using significant wave height at Newhaven

Type of RO plant	Tidal current / Wave Power (MW)	Hydrogen Fuel used?	Ratio of renewable scenario cost against conventional	Ratio against conventional with externalities	Impact of using significant wave height
No BSR	20.5/ 19.62	No	1.443	1.384	Potential to become financially viable when externalities are applied, as: •Twice as much wave power could be available •This scenario uses around 50% wave power •The shortfall is just under 45%. This scenario will almost certainly become viable once externalities are applied due to shortfall of around 38%.
Pelton Wheel	5.59/ 7.63	No	1.196	1.174	Likely to become financially viable without externalities, as: •Twice as much wave power could be available •This scenario uses almost 60% wave power, and •The shortfall is less than 20%.
Pressure Exchanger	4.28/ 6.33	No	1.188	1.168	Likely to become financially viable without externalities, as: •Twice as much wave power could be available •This scenario uses almost 60% wave power, and •The shortfall is less than 20%.
No BSR	15.84/ 15.41	Yes	1.57	1.507	Potential to become financially viable with externalities, as: •Twice as much wave power could be available •This scenario uses more than 55% wave power, and •The shortfall is just over 50%.
Pelton Wheel	4.88/ 6.67	Yes	1.209	1.187	Likely to become financially viable without externalities, as: •Twice as much wave power could be available •This scenario uses almost 60% wave power, and •The shortfall is less than 21%.
Pressure Exchanger	4.28/ 4.75	Yes	1.204	1.184	Potential to become financially viable without externalities, as: •Twice as much wave power could be available •This scenario uses around 50% wave power, and •The shortfall is around 20%.

Overall, it is considered that the use of significant wave heights would have a wide ranging impact on the financial viability of the scenarios, at both locations. Many of the scenarios have the potential to become financially viable, without the application of externalities.

That said, there are complex scenarios, where changes (e.g. in wave height) could act in such a way that they cause a disproportionate amount of water to be produced, or conversely fail to produce enough water.

As such, it is considered that, although at a simplistic level, the impact of wave height changes on the financial viability of scenarios have been presented above, the impact of wave height changes on modelled scenarios is worthy of further investigation, due to the complex nature of the impact that they could have on water production.

8.2.5 **Feedwater temperature.**

The feedwater temperature used in this model, was based on the monthly average temperature (detailed in Appendix B). It is, however, unlikely that the feedwater temperature will align itself exactly with this average, and so the maximum and minimum feedwater temperature profiles for Massawa[117] [Thomson, 2003b] and Eastbourne[118] were developed, and are shown below in Figure 131 and Figure 132, respectively.

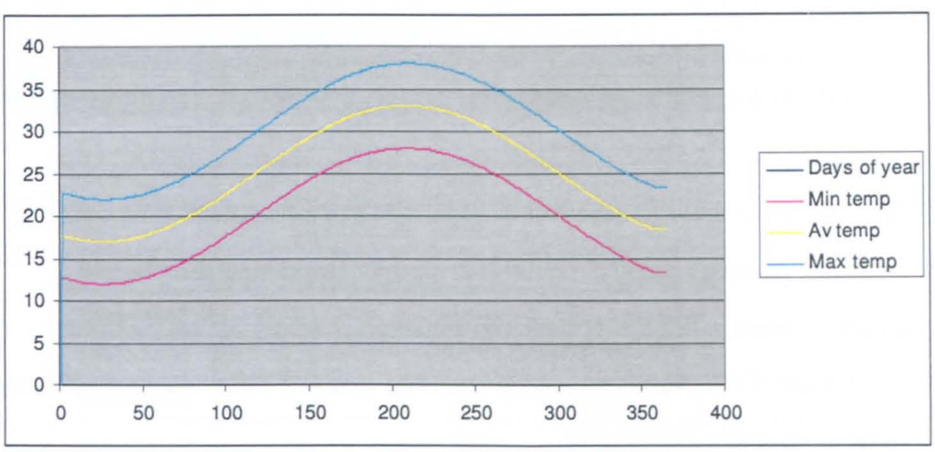

Figure 131: Maximum and minimum feedwater temperature profiles, for Massawa

Maximum temperature = 30+ 8 sin (2 π (*day of year*-118)/ 365))

[117] 5 degrees Celsius was estimated as the difference between Maximum and Average and Average and minimum, which allowed the equations for Maximum and Minimum temperatures as shown to be derived.

[118] The Eastbourne Maximum and Minimum temperatures were taken from the standard deviation seawater temperature range, available at http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/sea-temperature-and-salinity-trends/presentation-of-results/station-20-eastbourne.aspx?RedirectMessage=true [Last viewed on 7 August 2011]

Minimum temperature = 20+ 8 sin (2 π (*day of year*-118)/ 365))

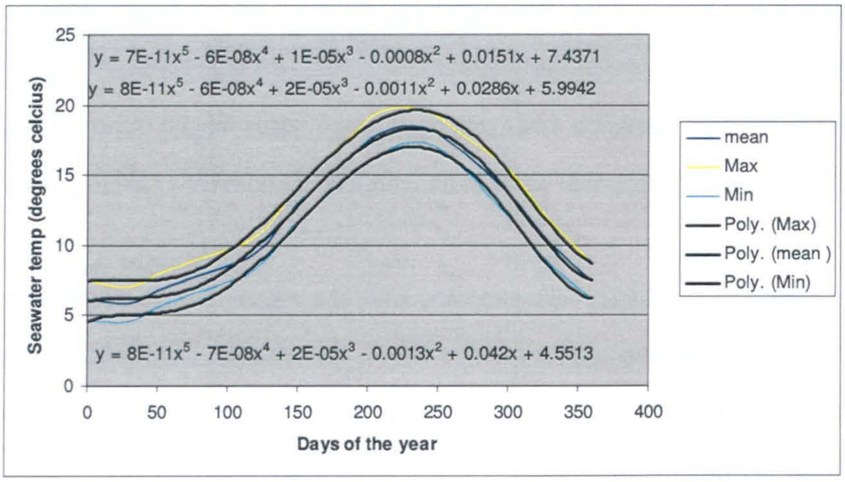

Figure 132: Maximum and minimum feedwater temperature profiles, for Newhaven/ Eastbourne.

As the feed water temperature increases, the permeate flow increases, but at the same time the salt passage will also increase, and *vice versa*[119].

Considering that the size of the RO plants and power sources (conventional and renewable) have been determined based on the average temperature, it can be seen that changes in the feedwater temperature could impact on the scenarios in the following ways:

1. For a lower-than-modelled feedwater temperature
    a. The scenarios ability to make enough water will require more energy per unit volume of water produced.
    b. There will be an impact on the cost of scenarios, as they will need to be scaled-up in size to meet user demands, when the water is at minimum temperature.
2. For a higher-than-modelled feedwater temperature
    a. An increase in reservoir volume will be required, due to a higher-than-anticipated volume of water produced.
    b. Less energy will be required per unit volume of water produced.

[119] Typically, when flow is increased by increased feed pressure, the permeate quality will improve due to a better salt-to-water passage ratio. This is because salt passage is not changed by feed pressure. But in the case of temperature, the salt passage is increased at a rate of approximately double the increase of permeate flow. This means that the permeate quality will get worse, even though the permeate rate is increasing. The only other issue of concern when operating at elevated temperatures, is membrane scaling. Many sparingly-soluble salts will come out of solution sooner at elevated temperatures, which in turn could lead to scaling on the membrane surface, which would then lead to lower flow and poorer rejection. In the majority of cases, the benefits of raising the temperature will outweigh the negatives. But in some cases, raising the temperature will lead to unacceptable permeate quality, or shorter membrane life.

c. The cost of conventional energy scenarios may reduce to such a level that renewable energy scenarios become less financially-attractive.

Since the scenarios could be significantly affected by changes in feedwater temperature, it is advised that the following are given consideration for further investigation:

- The minimum size ~~of RO plant and power source to continue to meet demand when the~~ feedwater temperature is low, and;
- The minimum size ~~of reservoir to provide adequate storage if the feedwater temperature is high~~ and the RO plant produces more water than expected.

8.2.6 **Impact of intermittent operation on RO plant costs.**

Intermittent operation of desalination plants is possible and has already been realised in smaller systems [Louw, 2001]. However, for large-scale seawater desalination plants, intermittent operation would lead to a reduction in economic performance as the investment of the desalination plant would not be amortized properly as shown below in Table 77 by the most financially attractive scenarios which require the RO plant to be more than four (4) times the size that would be required if they were operated continuously.

Table 77: Scenarios requiring large RO plants to overcome intermittency

Type of RO plant	Massawa			Newhaven		
	Power Source	Ratio of Scenario RO plant capacity Vs conventionally powered scenario.	Ratio against conventional with externalities	Power Source	Ratio of Scenario RO plant capacity Vs conventionally powered scenario.	Ratio against conventional with externalities
No BSR	Solar	2.7	1.01	Tidal Current	**4.1**	2.84
Pelton Wheel	Solar	2.4	1.39	Tidal Current	3.0	2.48
Pressure Exchanger	Solar	2.5	1.37	Tidal Current	3.3	2.43
No BSR	Solar + Wind	2.5	**0.85**	Tidal Current + Wind	1.8	1.47
Pelton Wheel	Solar + Wind	1.8	1.11	Tidal Current + Wind	1.8	1.36
Pressure Exchanger	Solar + Wind	1.6	1.19	Tidal Current + Wind	1.7	1.33
No BSR	Solar + Wave	1.6	**0.89**	Tidal Current + Wave	1.4	1.38
Pelton Wheel	Solar + Wave	1.4	1.06	Tidal Current + Wave	1.3	**1.17**
Pressure Exchanger	Solar + Wave	1.6	1.06	Tidal Current + Wave	1.3	**1.17**
No BSR	Solar + H_2	2.4	1.02	Tidal Current+ H2	3.7	2.99
Pelton Wheel	Solar+ H_2	1.5	1.18	Tidal Current+ H2	2.6	2.43
Pressure Exchanger	Solar+ H_2	1.5	1.17	Tidal Current+ H2	2.7	2.33
No BSR	Solar + Wind+ H_2	1.9	0.87	Tidal Current + Wind+ H2	1.2	1.44
Pelton Wheel	Solar + Wind+ H_2	1.2	0.98	Tidal Current + Wind+ H2	1.1	1.24
Pressure Exchanger	Solar + Wind+ H_2	1.6	1.02	Tidal Current + Wind+ H2	1.1	**1.18**
No BSR	Solar + Wave+ H_2	1.39	0.90	Tidal Current + Wave+ H2	1.3	1.51
Pelton Wheel	Solar + Wave+ H_2	1.2	1.01	Tidal Current + Wave+ H2	1.1	1.19
Pressure Exchanger	Solar + Wave+ H_2	1.1	1.01	Tidal Current + Wave+ H2	1.0	1.18

The plant's lifetime could also be reduced by increased scaling, fouling and corrosion [Rheinlander, 2007]. In reality, the overall energy consumption would increase, as temperature- and pressure would continuously change which would lead to efficiency losses within all components of the plants. Therefore, it is clear that there is some financial benefit to continuous operation of the RO plant beyond the reduced level of scaling up required to deliver the correct amount of water.

All RO plant scenarios modelled have been assumed to require membrane change every five years, but for a highly intermittent plant experiencing excessive fouling this could be as frequently as annually or bi annually (as experienced by CREST and the pilot RO plant in Riyadh, respectively), which is potentially a tenfold increase in the expenditure associated with membrane replacement. The impact on RO plant operation and costs will vary based on the power supply intermittency of each scenario, the degree of this impact is not well understood and is worthy of further investigation.

The methodology used to achieve constant operation in this research is hydrogen storage, and in some scenarios is competitive with the non-hydrogen storage equivalent (see section 6.4.4.1 'Stage 1 and 2 scenarios with hydrogen fuel at Massawa' for more detail of the CoFP methodology employed). The simplicity of the cost modelling, that uses the same O&M costs for non-hydrogen scenarios, which will experience many more interruptions to their operation, is, in light of the impact of intermittency on large-scale RO plants, probably unreasonable. There are several scenarios using hydrogen fuel, particularly those at Massawa with brine stream recovery and using primary and secondary power sources, as shown above at Table 77 with yellow highlights, where the RO plant is, in most cases, less than 1.6 times the size of a conventionally powered plant. These scenarios operate almost continuously and it is therefore reasonable to apply the non-intermittent operation RO plant maintenance costs.

The non-hydrogen fuel scenarios costs are probably slightly under estimated, due to the lack of intermittent operation maintenance contingency. The extent of the contingency required is not well understood and is recommended for further investigation to assess its potential impact on the two Massawa No BSR scenarios (highlighted in bold in Table 77), which were estimated to be financially viable when externalities were applied.

8.3 Potential improvements to the scenarios

The renewable energy scenarios were generally basic and simplistic, and it was evident that there were improvements that could be made to the scenarios, by making them more sophisticated, efficient and location-specific.

These potential improvements could have an impact on the results, as mentioned at section 1.1.1.

Some of these potential improvements are included below in Table 78 with their potential impacts.

Table 78: Potential improvements

Basic Model used	Improvement	Further Improvement	Expected result of improvements
Electrically driven RO plant based on the being what would be employed if conventionally produced electricity was used as the energy source.	Selection of the most appropriate renewable energy desalination technology based on appropriate criteria. See Appendix B 'RO Plant Selection' for greater details.		Improved efficiency and confidence in operation with reduction in complexity.
PV Solar – fixed axis	Single axis	Dual Axis	Greater efficiency but increasing technical complexity and costs.
Solar PV	Concentrated Solar Power (CSP)	CSP with molten salt	Increased complexity, but need greater understanding of water use required. Reduction in the physical area required, and potentially reduced cost at large scale.
Tidal stream – large conversion device (SeaGen) employed.	Use tidal stream device better suited to slower tidal current speeds at Newhaven.		Greater efficiency but increasing technical uncertainty, due to development status, and costs.
Tidal stream – sited near shore at Newhaven	Tidal stream – sited further off shore at Newhaven	Tidal stream – sited at best site on south coast (with best tidal range).	Improved environmental conditions for power production but increasing vulnerability to marine environment, and therefore increased design, build and operating costs. Also greater losses in power due to need to transport power over longer distances.
Wind – Furhlander turbine on land at Newhaven	Wind – Furhlander turbine near shore	Wind – Furhlander turbine off shore	Improved wind speeds for power production but increasing vulnerability to environment, and therefore increased design, build, operating and maintenance costs. Also greater capital costs and losses in power due to need to transport power over longer distances.
Wind – Furhlander turbine on land at Massawa	Wind – Furhlander turbine on land at site in Eritrea with better wind speeds.		Improved wind speeds for power production but will also require power distribution infrastructure. This will incur losses in power due to the need to transport power over longer distances.
Wave – Wave Dragon near shore	Wave – Wave Dragon off shore	Wave – Wave Dragon at best local wave site	Improved environmental conditions for power production, but increasing vulnerability to marine environment, and therefore increased design, build and operating costs. Also greater costs and losses due to need to transport power over longer distances.
Hydrogen fuel with 22% round trip efficiency.	Redox cell – quoted as having round trip efficiency of 80%.		Improved efficiency and probably ease of operation, storage, infrastructure, etc. Technologies are still in early stages of development on large scale, and costs are not yet fully understood.
Hydrogen fuel being limited to maintaining operation of the RO plant at maximum output.	Over-sizing the RO plant to allow the hydrogen fuel to maintain operation at optimum efficiency.		Potential to reduce cost based on the improved efficiency of water production, based on the assumption that increasing efficiency outweighs cost of increasing size of RO plant.
Simple scale-up of scenario power plant and RO plant to ensure 100% of the water required by users is delivered.	Scale-up power plant and RO plant only to deliver water required		Potential to identify optimum power plant and RO plant combination, which will probably be cheaper than the simple scaled-up options identified.
Each renewable energy source is located at a single location, source, recommended that the impact of its use on the ability to maintain the operation of plant that prefers to run constantly, such as RO, is investigated further	Disaggregate individual power sources to minimise intermittency i.e. that tidal maxima occur at different times at different sites, and similarly for wind, though the geographical spread would be very much larger.	Combine disaggregated power sources to minimise intermittency/ reliance on energy storage.	Potential to identify optimum power plant and RO plant combination, which will could be cheaper than the simple scaled-up options identified if the costs associated with disaggregation do not exceed the benefits.

9 Conclusion

The objective of this research was to assess the viability of renewable energy to completely displace a conventional power source, and provide a fundamental and significant human need.

To make this assessment, this research modelled various scenarios at Massawa in Eritrea and Newhaven in South East England, with a view to addressing the water needs of 50,000 people using various RO plant types, such as:

- A simple plant with No Brine Stream Recovery (BSR)
- A BSR Plant with a Pelton Wheel, to re-use energy captured from the brine stream
- A BSR Plant with Pressure Exchanger mechanism to re-use energy captured from the brine stream.

The renewable energy sources, and combinations of these were investigated, as indicated below:

- At Massawa
    - Solar Energy.
    - Solar and Wind Energy.
    - Solar and Wave Energy.
- At Newhaven
    - Tidal Current Energy.
    - Tidal Current and Wind Energy.
    - Tidal Current and Wave Energy.
- Hydrogen Fuel, considered at both Massawa and Newhaven.

The research has demonstrated that a significant and fundamental human need can be addressed by using renewable energy.

All the combinations of renewable energy sources modelled were able to meet the water requirements of 50,000 people, although there was a significant difference in the efficiency of water production in scenarios, due to the quantity, and mix of energy sources used.

With respect to the cost associated with meeting such a need, the most financially-attractive scenario was at Massawa, using solar power and a simple No BSR RO plant.

A plant such as this:

- Minimises the difficulties associated with the operation of very complex machinery (required to implement many of the other modelled scenarios), and
- Improves the prospects for Massawa to have security over its water supply.

A simple précis of the most financially-attractive scenarios, is presented below for Massawa and Newhaven, in Table 79 and Table 80 respectively showing:

- The type of RO plant
- The renewable power source employed by the scenario
- The total renewable power capacity installed for the scenario
- The 'Ratio' of cost of the renewable-powered scenario to the conventionally-powered equivalent, over 25 years. (Less than '1' is taken as financially viable), and
- The 'Ratio' of cost of the renewable powered scenario, to the conventionally powered equivalent over 25 years, when the externalities associated with conventional energy was taken into account. Once again, less than '1' is taken as being financially viable.

Table 79: Most financially favourable option at Massawa

Type of RO plant	Renewable Power Sources	Total power installed (kW)	Ratio of cost of renewable to conventional energy scenario	Ratio of cost of renewable to conventional energy scenario taking externalities into account.
No BSR	Solar and Wind	27,301	1.227	0.85

Table 80: Most financially favourable option at Newhaven

Type of RO plant	Renewable Power Sources	Total power installed (kW)	Ratio of cost of renewable to conventional energy scenario	Ratio of cost of renewable to conventional energy scenario taking externalities into account.
Pressure Exchanger	Tidal Current and Wave	10603	1.19	1.17

It was noteworthy that:

- There is a significant difference in the cost of scenarios, due to the quantity, and combination of energy sources used
- At Massawa, the following scenarios become financially viable, when the externalities associated with the use of diesel fuel were applied:
  - Four of the six No BSR RO plant options, and
  - The Pelton Wheel BSR RO plant with wind power and hydrogen fuel.

To be financially viable in the 'real world', (to realise the cost benefit of these externalities), would require the support of a scheme such as the 'Clean Development Mechanism', which acknowledges the cost associated with the externalities of conventional power use.

None of the renewable energy scenarios modelled at Newhaven, when compared to the modelled coal-fired plant with carbon capture and storage (CCS) plant, were financially viable over the life of the facility.

The most financially-attractive scenario at Newhaven (shown above in Table 79) was 19% and 17% too expensive, without and with externalities, respectively.

9.1 Application of NPV

The Net Present Value (NPV) methodology, (which is the generally-accepted way of making infrastructure investment decisions), considers money in the future to be cheaper than today, so any option with a large initial outlay but reduced on-going costs will appear inferior to options with a small initial outlay and significant on-going costs.

The use of the NPV methodology was applied to assess the viability of the most financially-attractive scenario (a No BSR RO plant at Massawa with solar and wind energy).

The application of NPV (with a 7% discount rate) changed the 'break even' point of the above of about 20 years, and almost £102 million in profit over the 25-year life of the installation, into a loss in excess of £90 million.

As stated previously, the Stern Report is clear that the option to delay the implementation of renewable energy projects is no longer reasonable, but the standard NPV evaluation methodology, with its relatively high discount rate, does not acknowledge this. In fact, it actively encourages the evaluator to delay spending for as long as possible.

It is considered that the NPV as a method of evaluating the long-term costs of renewable scenarios, would benefit from further consideration of the discount rate employed in line with the Stern Report's contention that future generations should not be relied upon to manage the climate change impacts of previous generations' decisions, and application of the Clean Development Mechanism (CDM) to fully acknowledge the:

- Impact of delay, in light of the potential prospects of climate change and
- The full externalities associated with 'business as usual'.

9.2 Scrutiny of findings

The potential to fail to meet the water demand profile of local users was investigated in terms of the shortfall against their demands if the reservoir were empty at the start of operation. For the most financially-attractive scenarios at each site, the shortfall was around 3.5% and 0.7% for Massawa and Newhaven, respectively.

As such, it is considered that:

- The planning of the start-time of the facility would need to be organised to align with the best power production conditions at each site, and/ or

- The transition to using the RO plant should be organised such that, the reservoir has enough water to satisfy the users' initial demand for water before the water produced by the RO plant is relied upon.

The impact of polynomial approximations on the results was assessed and was shown to have a limited effect on the results at Massawa, (by altering the majority of the results with externalities applied), and no effect at all on the Newhaven scenarios.

There were also six main variables that were investigated further within this research, in terms of scenario design, and their potential to vary from the modelled profile:

- The cost of diesel fuel
- Solar power
- Wind speed
- Wave height
- Feedwater temperature, and
- Impact of intermittent operation on RO plant costs.

The results were found to be highly susceptible to a relatively modest increase in diesel fuel prices over the life of the installation at Massawa.

Although the 5% annual increase in diesel fuel costs modelled only made scenarios financially viable when externalities were applied, it is considered likely that the diesel fuel cost increase expected over the next 25 years will:

- Be much higher than the 5% annual increase modelled, and
- Significantly improve the prospects of financial viability for scenarios at Massawa.

The impacts of variations in solar power, wind speed and wave height have been considered and it has been concluded that their potential to vary would have a significant impact on the modelled scenarios that are considered financially viable.

The impact of feedwater temperature changes have not been fully assessed, and a greater understanding of the practicalities of implementing large-scale solar power installations, and wind speed and wave height changes, is needed to assess the impact on the power produced.

The intermittency of operation due to varying power input has the potential to increase the maintenance costs. As such the financial viability of the scenarios not using hydrogen fuel to minimise intermittent RO plant operation has probably been overestimated and has the potential to negatively affect the financial viability of two of the Massawa scenarios that did not use hydrogen fuel that were estimated to be financially viable when externalities were applied.

It is considered that these variables, and their impacts on the modelled scenarios' financial viability, are worthy of further investigation.

9.3 Potential scenario improvements

There are also several options available to enhance the renewable energy scenarios, by:

- Making them more efficient, and
- Making the best use of local resources.

This also potentially increases the complexity of the scenarios, making them more difficult to implement and operate effectively. This is worthy of further investigation.

The overall conclusions are that:

- It is possible to desalinate water for human consumption at Massawa, in Eritrea and Newhaven, using renewable energy
- This is financially viable at Massawa, when the externalities of diesel fuel are considered
- The costs of using renewable energy at Newhaven are (at best) 17% greater than when using conventional energy
- There is significant scope to improve the scenarios, to make many of them more financially-attractive than identified within this research.

10Recommendations for further work

It is suggested that:

- The operability and maintainability of the more financially-attractive scenarios at Massawa be investigated further, to better understand the complexities of implementation, including:
    - The transition to starting-up the facility
    - Operating methodology, and
    - Possible failure modes.
- The impact of the practical use of solar power, the variability of wind speed, and the variability of wave height, are investigated further, to see how they affect the viability of scenarios
- More sophisticated scenarios (as described at Table 77) are investigated for viability
- The installed power limitations for scenarios that employ less-predictable power sources, such as wind, are investigated further to allow the design to accommodate any reasonably-expected fluctuations
- The synchronisation of power supplies in the combinations modelled, is investigated for practical application
- A method of evaluating the financial viability of renewable-powered infrastructure projects, which acknowledges that delaying implementation (as the NPV methodology encourages) is unreasonable, is considered
- The impact of feedwater temperature on renewable-powered scenarios is investigated further
- The application of a Project of this type (municipal renewable-powered reverse osmosis) is considered for application to the Clean Development Mechanism where the impact of externalities would be acknowledged.
- The application of other financial incentives, such as FiT (Feed in Tariff) and ROCs (Renewable Obligation Certificates) are also considered to acknowledge the saving in externalities by employing renewable energy to replace conventional energy.
- Combined scale-up factors for RO plant and power plant are studied, in comparison to scaling-up of the RO plant and power plant individually, to deliver the correct volume of water.
- The proper matching of desalination systems with their local renewable energy power sources, including direct solar desalination with heat powered pumping, and heat/ energy storage is investigated further.

- The impact of the use of disaggregation of energy sources are studied further to assess their ability to maintain constant power supply.
- The O&M costs for the RO plant associated with intermittent operations are studied further to ensure that the credit for non-variable power supply scenarios fully reflect the benefits to RO plant life.
- That the comparison between large municipal RO plants and combinations of smaller (less intermittency susceptible) RO plants switching on and off as available power allows is investigated further.

11 References

AA (The Automobile Association). October 2011. 'Fuel Price Report' for October 2011. Available at http://www.theaa.com/motoring_advice/fuel/ [Last viewed on 27 October 2011].

Aaron L. November 2008. 'North Africa Regional SWRO Desalination Project : Big Breakthrough Technology Reducing Energy And Overall Costs'. Available at http://www.articleclick.com/Article/North-Africa-Regional-SWRO-Desalination-Project-Big-Breakthrough-Technology-Reducing-Energy-and-Overall-Costs/1064395 [Last viewed on 7 August 2011].

ABP MER (Associated British Ports Marine Environmental Research). 2011.

a) 'WEBvision – Renewables (Wind)'. Available at http://vision.abpmer.net/renewables/map_default.phtml?config=wind&resetsession=groups,resultlayers [Last viewed on 7 August 2011].
b) 'WEBvision – Renewables (Wave)'. Available at http://vision.abpmer.net/renewables/map_default.phtml?config=wave&resetsession=groups,resultlayers [Last viewed on 7 August 2011].

Abrams L. July 2001 'Water for Basic Needs' (Commissioned by the World Health Organisation as input to the 1st World Water Development Report). Available at http://www.africanwater.org/Documents/BasicNeeds.PDF [Last viewed on 7 August 2011].

Ackerman F. July 2007. 'Debating Climate Economics: The Stern Review vs. Its Critics' A Report to Friends of the Earth by the Global Development and Environment Institute, Tufts University, Medford MA 02155, USA Published July 2007. Available at http://sei-us.org/Publications_PDF/SEI-FOE-DebatingClimateEcon-07.pdf [Last viewed on 7 August 2011].

AEA. September 2002. 'The Feasibility, Costs and Markets for Hydrogen Production – A study for British Energy undertaken by AEA Technology. Available at http://www.british-energy.com/documents/The_Feasibility,_Costs_and_Markets_for_Hydrogen_Production.pdf [Last viewed on 7 August 2011].

Alpheus. 'Case Study – Flag Fen'. Alpheus web site. Available at http://www.alpheus.co.uk/flag-fen/ [Last viewed on 7 August 2011].

Andrews W.T., Pergande W. F., and McTaggart G. S. 2001. 'Energy performance enhancements of a 950m^3/d seawater reverse osmosis unit in Grand Cayman'. Desalination 135 (2001) 195 – 204.

APS. June 2011 'Direct Air Capture of CO_2 with Chemicals A Technology Assessment for the American Physical Society (APS) Panel on Public Affairs'. Available at http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=244407 [Last viewed 1 April 2012]

Atikol U., Hikmet S., Aybar S. 2005. 'The feasibility analysis of RO systems'. Desalination 184 (2005) 253–258. Available at http://www.desline.com/articoli/6765.pdf [Last viewed on 7 August 2011].

Bank of England. May 2012. Overview of the Inflation Report. Available at http://www.bankofengland.co.uk/publications/Pages/inflationreport/infrep.aspx [Last viewed on 15 July 2011].

Barnes I., Sear L. December 2004. 'Ash Utilisation from Coal-Based Power Plants'. Available at http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file19179.pdf [Last viewed on 7 August 2011].

Barry R. G., Chorley R. J. 2003. 'Atmosphere, Weather and Climate'. Routledge. p. 113. ISBN 0-415-27171-1. Available at http://books.google.com/?id=MUQOAAAAQAAJ&pg=PA115. [Last viewed on 7 August 2011].

Bauer C., Heck T., Dones R., Mayer-Spohn O., Blesl M. March 2008. New Energy Externalities Developments for Sustainability (NEEDS) INTEGRATED PROJECT. Priority 6.1: Sustainable Energy Systems and, more specifically, Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy. Deliverable n° 7.2 - RS 1a "Final report on technical data, costs, and life cycle inventories of advanced fossil power generation systems". Available at http://gabe.web.psi.ch/pdfs/Needs/NEEDS_RS1a_D7-2.pdf [Last viewed on 7 August 2011].

Berner E. K., Berner R. A. 1987. 'The Global Water Cycle: Geochemistry and Environment', Table 2.1, p. 13. Reproduced by permission of Prentice Hall, Inc., Englewood Cliffs, N.J. via encyclopaedia Britannica 2002 Standards edition.

Bewlwater. Bewlwater reservoir – facts and figures'. Available at http://www.bewlwater.co.uk/kent/file/Bewl%20Water%20Reservoir%20Factsheetsv2.pdf [Last viewed on 7 August 2011]

Blesl M., Wissel S., Mayer-Spohn O. August 2008. 'Private costs of electricity and heat generation'. CASES (Cost Assessment of Sustainable Energy Systems). Deliverable No D.4.1 'CASES is a project co-funded by the European Commission within the Sixth Framework Programme (2002-2006). Available at http://www.feem-project.net/cases/downloads_deliverables.php [Last viewed on 7 August 2011]

Boyle J. W. C. M.I.C.E., P.Eng. April 2008. 'Design, Construction and repair of Potable Water Reservoirs'. Proceedings of the British Columbia Water & Waste Association Annual Conference, Whistler.

BP (British Petroleum). 1979. *Oil crisis ... again ?*. Report.

Brito-Melo A., J. Huckerby J. 2008/ 2009.'The State of Renewable Energies in Europe', 8th EuObserv'ER Report (Paris), p. 77; eds., Ocean Energy Systems Implementing Agreement -OES-IA Annual Report 2009 (Paris: IEA, 2009); "Tidal Power Turbine Deployed on Canada's East Coast," RenewableEnergyFocus.com, 17 November 2009; Japan and India from "Ocean Energy Developments," RenewableEnergyWorld.com, 18 September 2009.

Brown D. April 2007. 'Turning Sea water into drinking water ruled out as too expensive'. The Times. Available at http://www.timesonline.co.uk/tol/news/science/article1647472.ece [Last viewed on 7 August 2011].

Butay D. F., Miller M. T. April 2008. 'Maximum Peak Power Tracker: A Solar Application - A Major Qualifying Project Report,' Worcester Polytechnic Institute, Available at http://www.wpi.edu/Pubs/E-project/Available/E-project-042408-181823/unrestricted/PPTReport.pdf [Last viewed on 7 August 2011]. See page 17

Wind Site Evaluation. 2010. 'How to estimate the Electricity Production of a Wind Farm'. Wind Site Evaluation website. Available at http://www.wse.ie/estimate-electricity-production-wind-farm.php [Last viewed on 7 August 2011].

Carbon Retirement Limited. December 2009. 'The Cost Efficiency of Offsetting through the Clean Development Mechanism. Carbon Retirement'. Available at http://www.carbonretirement.com/sites/default/files/The%20efficiency%20of%20offsetting%20with%20CDM%20credits.pdf [Last viewed 9 July 2012].

Carbon Solution Credit. 2012. 'CDM After 2012'. Available at http://www.carbonsc.com/cscb/index.php?option=com_content&view=article&id=32:cdm-after-2012&catid=9:kyoto-protocol&Itemid=4 [Last viewed 7 April 2012].

CAT (Centre for Alternative Technology). 2010. 'ZeroCarbonBritain2030. A New Energy Strategy. The second report of the Zero Carbon Britain project'. ISBN 978-1-902175-61-4. Available at http://www.zerocarbonbritain.org/ [Last viewed on 7 August 2011].

CEFAS. May 2011. 'Station 20: Eastbourne'. The Eastbourne Maximum and Minimum temperatures were taken from the standard deviation seawater temperature range, available at http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/sea-temperature-and-salinity-trends/presentation-of-results/station-20-eastbourne.aspx?RedirectMessage=true [Last viewed on 7 August 2011]

CIA – Central Intelligence Agency. 2012. 'The World Factbook – Africa. Eritrea' Available at https://www.cia.gov/library/publications/the-world-factbook/geos/er.html [Last viewed on 10 July 2012].

Clean Air Task Force. June 2001. 'Cradle to Grave: The Environmental Impacts from Coal'. Available at http://www.catf.us/resources/publications/files/Cradle_to_Grave.pdf [Last viewed on 7 August 2011].

Cornett. A. September 2009. 'Guidance for Assessing Tidal Current Energy. Annex II – Task 1.2 Generic and site related tidal data. October 2008'. Prepared by the Canadian Hydraulics Centre. Document number TO2-1.2. Available at http://www.iea-oceans.org/_fich/6/Report_T02-1.2.pdf [Last viewed on 7 August 2011].

Cramer B., Andruleit H. 2009. 'Energy Resources 2009. Reserves, Resources, Availability. Crude Oil, Natural Gas, Coal, Nuclear Fuels, Geothermal Energy. Status 10.11.2009'. Bundesanstalt fur Geowissensschaften und Rohstoffe (BGR). The Federal Institute for Geosciences and Natural Resources. ISBN 978-3-9813373-9-6. Available at http://www.bgr.bund.de/EN/Themen/Energie/Downloads/Energierohstoffe_2009_Teil2_en.pdf?__blob=publicationFile&v=2 [Last viewed on 7 August 2011].

Crisp G. 2006. 'Australia's first big plant thinks "green"'. The Desalination & Water Reuse Quarterly- November/ December 2006 – Volume 16/No 3. Available at http://www.energyrecovery.com/UserFiles/file/archives/news/documents/DWR_PerthSWROPlant.pdf [Last viewed on 7 August 2011].

Cru J. 2008. 'Ocean wave energy: current status and future perspectives' [Green Energy and Technology]. Garrard Hassan and Partners Limited. Bristol. ISBN 978-3-540-74894-6. See page 100.

CTA (International Center for Technology Assessment). Jan 2005. 'Gasoline Cost Externalities: Security and Protection services. An update to CTA's Real Price of Gasoline Report'. Available at http://www.icta.org/doc/RPG%20security%20update.pdf [Last viewed on 7 August 2011].

de la Peña M. E. August 2006. 'Identification and evaluation of reuse-oriented sanitation concepts in African Urban Areas Case study: Massawa, Eritrea'. MASTER THESIS, Hamburg University of Technology. Available at http://www2.gtz.de/Dokumente/oe44/ecosan/en-reuse-oriented-sanitation-concepts-2006.pdf [Last viewed on 7 August 2011].

Diesel service and Supply. 2011. 'Approximate diesel fuel consumption chart' Available at http://www.dieselserviceandsupply.com/Diesel_Fuel_Consumption.aspx [Last viewed on 7 August 2011].

Division of Water Resource Management, Florida Department of Environmental Protection. April 2010. 'Desalination in Florida: A Brief Review of the Technology, Environmental Issues and its Implementation'. Available at http://www.dep.state.fl.us/water/docs/desalination-in-florida-report.pdf [Last viewed on 7 August 2011].
Table 3-5, on page 34, which is a summary of 'Estimated Costs to Build and Operate RO Desalination Facilities at Port Everglades, Lauderdale, and Fort Myers Power Plant Sites'. (Metcalf & Eddy, 2006).

DTI (Department of Trade and Industry). 'Overview of Modelling of the Relative Electricity Generating Costs of Different Technologies'. Available at http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file31936.pdf [Last viewed on 7 August 2011].

DTI. 2003 WAVE AND MARINE CURRENT ENERGY STATUS AND RESEARCH AND DEVELOPMENT PRIORITIES | 2003 DTI report number FES-R-132 AEAT report number AEAT/ENV/1054 Available at http://www.iea-oceans.org/_fich/6/IEA-OES_Wave_and_Tidal_report.pdf [Last viewed on 7 August 2011].

Ebert S., Metschies G. P., Schmid D., Wagner A. December 2009. 'International Fuel Prices 2009 6th Edition'. The Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. Available at http://www.gtz.de/de/dokumente/gtz2009-en-ifp-full-version.pdf [Last viewed on 7 August 2011].

ECF (European Climate Foundation). March 2011. 'Roadmap 2050: a practical guide to a prosperous, low-carbon Europe', developed by the ECF with contributions from McKinsey, KEMA, Imperial College London and Oxford Economics, available at http://www.roadmap2050.eu/ [Last viewed on 7 August 2011].

Ekins-Daukes N. J. June 2009 Grantham Institute for Climate Change. Briefing Paper No. 1. 'Solar energy for heat and electricity: the potential for mitigating climate change'. Available at https://workspace.imperial.ac.uk/climatechange/public/pdfs/GranthamJune.pdf [Last viewed on 7 August 2011].

Enerdata. 2011. 'Enerdata Global Energy Statistical Yearbook'. Available at http://yearbook.enerdata.net/ [Last viewed on 7 August 2011]. This page states that 12952Mtoe were consumed in 2010, which equates to 149468.76TWh. The International Energy Agency Unit converter was employed for this calculation which is available at http://www.iea.org/stats/unit.asp [Last viewed on 7 August 2011].

Energy Watch Group. November 2008. 'Renewable Energy Outlook 2030'. Available at www.energywatchgroup.org/Renewables.52+M5d637b1e38d.0.html [Last viewed on 7 August 2011].

Environment Agency. March 2010. 'Ensuring Water for All Scoping Study Final Report'. Page 61. Available at http://www.waterwise.org.uk/data/2010_Waterwise_ensuring_water_for_all.pdf [Last viewed on 7 August 2011].

EREC (European Renewable Energy Council). April 2010. 'Rethinking 2050. A 100% Renewable Energy Vision for the European Union'. Available at www.rethinking2050.eu/ [Last viewed on 7 August 2011].

Euroheat & Power. 'Renewables in district heating and cooling' brochure available at http://www.localpower.org/documents/reporto_ehp_renewablesandde.pdf [Last viewed on 7 August 2011].

ExternE. 2003 'European Commission EUR 20198—External Costs Research results on socio-environmental damages due to electricity and transport' ISBN 92-894-3353-1 is available at http://www.externe.info/externpr.pdf [Last viewed on 7 August 2011].

FAO (Food and Agriculture Organisation).
a) 'Chapter 3. The use of water in agriculture'. Available at http://www.fao.org/DOCREP/006/Y4683E/y4683e07.htm [Last viewed on 7 August 2011].
b) '3. Global and regional food consumption patterns and trends'. Available at http://www.fao.org/DOCREP/005/AC911E/ac911e05.htm [Last viewed on 7 August 2011].

FAO (Food and Agriculture Organization). 1996. Food requirements and population growth. Available at http://www.fao.org/docrep/003/w2612e/w2612e4a.htm [Last viewed on 7 August 2011].

FAO (Food and Agriculture Organization). 2003. 'World Agriculture: Towards 2015/ 2030. An FAO perspective 2003'. Available at http://www.fao.org/DOCREP/005/Y4252E/y4252e04b.htm [Last viewed on 7 August 2011].

Florin N., Fennell P. November 2010. 'Carbon capture technology: future fossil fuel use and mitigating climate change'. Grantham Institute for Climate Change Briefing paper No 3. Available at https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Briefing%20Papers/Grantham%20Briefing%20paper_Carbon%20Capture%20Technology_November%202010.pdf [Last viewed on 7 August 2011].

Fröberg E. 2006 'Current Power Resource Assessment - A study of selected sites in Sweden and Norway'. Available at http://uu.diva-portal.org/smash/record.jsf?pid=diva2:460586 [Last viewed on 7 August 2011].

Gebremedhin N. 6-8 December 2007. 'Asmara, Africa's Secret Modernist City'. Prepared for 'African Perspectives: Dialogue on Urbanism and Architecture', The Faculty of Architecture, Delft. Available at http://www.bk.tudelft.nl/fileadmin/Faculteit/BK/Actueel/Symposia_en_congressen/African_Perpectives/Programme/Built_Heritage/doc/APD_wp_5_gebremedhin_paper.pdf [Last viewed on 7 August 2011].

Geisler P., Krumm W., Peters T.A. 2001. 'Reduction of the energy demand for seawater RO with the pressure exchange system PES', Desalination 135 (2001) 205-210.

GENI. (Global Energy Network Institute). 2009. 'Ocean Energy Technologies for Renewable Energy Generation, August 2009, Peter Meisen President, Global Energy Network Institute (GENI) available at http://www.geni.org/globalenergy/research/ocean-energy-technologies/Ocean%20Energy%20Technologies.pdf [Last viewed on 7 August 2011]. Source of diagram:

Gerling S. L. 2001. 'Commission of the European Communities Directorate-General for Energy and Transport ALTENER PROGRAMME - Renewable Energy Driven Desalination Systems – REDDES (Contract number 4.1030/Z/01-081/2001) Technical analysis of existing RES desalination schemes Sustainable Development Project GmbH Hellas May 2002'.

Gilau A. M., Mitchell J. Small M. J. 2006. 'Designing Cost-Effective Sea Water Reverse Osmosis System under Optimal Energy Options for Developing Countries'. Proceedings of the International Conference on Renewable Energy for Developing Countries. Available at http://www.udc.edu/cere/docs/GilauSmall_Paper_ICRED06.pdf [Last viewed on 7 August 2011].

Glennon R., Reeves A. M. 2010. 'Solar Energy's Cloudy Future' by published in Arizona's Journal of Environmental Law and Policy Volume 1, No. 1 2010. Available at http://ajelp.com/documents/GlennonFinal.pdf [Last viewed on 7 August 2011].

Habtetsion S., Ghebrehiwet D., Van Buskirk R., Lebassi B. 2002. 'The Potentials of Wind Energy Applications in Eritrea'. World Renewable Energy Congress VII, Cologne, Germany. Available at http://www.punchdown.org/rvb/wind/AFREPRENArtcl200207.html [Last viewed on 7 August 2011].

Hagos B. May 2011 'The Asmirano report 'Eritrea's 20th Anniversary Comprehensive Report Card' Monday, 16 May 2011. Available at http://asmarino.com/articles/1034-eritreas-20th-anniversary-comprehensive-report-card. [Last viewed on 7 August 2011].

Harrabin R. 30 August 2010 at 09:00hrs and Mon, 6 Sep 2010, 21:30hrs. 'Uncertain Climate' Radio 4 .The BBC's Environmental Analyst reporting on whether his own reporting - and that of others - has adequately told the whole story about global warming, which is available at http://www.bbc.co.uk/programmes/b00tj525 [Last viewed on 7 August 2011].

Harrison D. 13 June 2004. 'Its official, the south east has less water per head than Sudan'. The Daily Telegraph. Available at http://www.telegraph.co.uk/news/uknews/1464400/Its-official-the-South-East-has-less-water-per-head-than-Sudan.html [Last viewed on 7 August 2011].

Hendryx M., Ahern M. M. July–August 2009. 'Mortality in Appalachian Coal Mining Regions: The Value of Statistical Life Lost'. SYNOPSIS Public Health Reports / Volume 124 available at http://wvgazette.com/static/coal%20tattoo/Mortality%20AppCoalRegions.pdf [Last viewed on 7 August 2011].

Hill J. S. 2011. 'Installed Wind Power Capacity Up 21% Globally in 2011. Clean Technica.com web page available at http://cleantechnica.com/2012/02/08/installed-wind-power-capacity-world/ [Last viewed on 7 August 2011].

Hind M. May 2007 'Municipal effluent: Waste stream or resource?' Presentation to the IWA, which provides alternative options for the reuse of wastewater.

Hirscher M. 2010. 'Handbook of Hydrogen Storage – New Materials for Future Energy Storage'. WILEY-VCH. ISBN: 978-3-527-32273-2.

HM Treasury. July 2011 'The Green Book. Appraisal and Evaluation in Central Government. Available at http://www.hm-treasury.gov.uk/d/green_book_complete.pdf [Last viewed on 7 August 2011].

Hvistendahl M. December 2007. 'Coal Ash Is More Radioactive than Nuclear Waste - by burning away all the pesky carbon and other impurities, coal power plants produce heaps of radiation'. The Scientific American. Available at http://www.scientificamerican.com/article.cfm?id=coal-ash-is-more-radioactive-than-nuclear-waste [Last viewed on 7 August 2011]

Hordeski M. F. 2009. 'Hydrogen and Fuel Cells: advances in transportation and power'. Published by the Fairmont Press. ISBN 0-88173-562-0.

House K. Z., Harvey C. F., Aziz M. J., and Schrag D. P. January 2009. 'The energy penalty of post-combustion CO_2 capture & storage and its implications for retrofitting the U.S. installed base'. Journal of Energy & Environmental Science Advance Articles DOI: 10.1039/b811608c. Energy & Environmental Science. Available at http://schraglab.unix.fas.harvard.edu/publications/CV93.pdf [Last viewed on 7 August 2011].

Howden D. July 2011. 'Fears that Eritrea may be hiding its famine victims from the world', The Independent. Available at http://www.independent.co.uk/news/world/africa/fears-that-eritrea-may-be-hiding-its-famine-victims-from-the-world-2328668.html [Last viewed on 7 August 2011].

IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 7-22. Available at http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf [Last viewed on 7 August 2011].

Isaacs J.D., Seymour R.J. 1973. 'The ocean as a power source'. International Journal of Environmental studies, Vol. 4, no. 3, pp. 201-205.

Jacobson M., Delucchi M. Nov 2009 - A Plan for a Sustainable Future - How to get all energy from wind, water and solar power by 2030. Stanford University. Scientific American. Available at http://www.scientificamerican.com/article.cfm?id=a-path-to-sustainable-energy-by-2030 [Last viewed on 7 August 2011].

Kanellos M. September 2009. 'Pelamis Wave Power Jettisons Its CEO, Rough Waters Ahead?' available at http://www.greentechmedia.com/green-light/post/pelamis-wave-power-jettisons-its-ceo-rough-waters-ahead [Last viewed on 7 August 2011].

Keramane A. September 2008 Totally Renewable Electricity Supply: a European/Trans-European Example published in medenergie N°27 –available at http://transnational-renewables.org/Gregor_Czisch/projekte/Medenergy-Article_Sept2008.pdf [Last viewed on 7 August 2011].

a) Page 10 Section 5.2. 'Costs of Solar Electricity from Photovoltaic Generation.
b) Page 10 Section 5.1. 'Costs of Wind Energy'.

Lachish U. March 2003. 'Optimizing the Efficiency of Reverse Osmosis Seawater Desalination'. Available at http://urila.tripod.com/Seawater.htm [Last viewed on 7 August 2011].

Lasher S., McKenney K., Sinha J, Ahluwalia R., Hua T., Peng J. K. December 2009. 'Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications'. Report to: United States Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen, Fuel Cells & Infrastructure Technologies Program. December 2009. 'Available at http://www.tiaxllc.com/reports/TIAX_Compressed%20H2%20Storage_Combined%20Report_final2.pdf [Last viewed on 7 August 2011].

Loster M., 2010. 'Total Primary Energy Supply – From Sunlight'. Available at http://www.ez2c.de/ml/solar_land_area/ . [Last viewed on 7 August 2011].

Louw G. J. April 2001. 'DEVELOPMENT OF A SOLAR POWERED REVERSE OSMOSIS PLANT FOR THE TREATMENT OF BOREHOLE WATER'. WRC Report No 1042/1/01. Available at http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/1042-1-01.pdf [Last viewed on 7 August 2011] which reported that a 750 litre/ day brackish water RO plant performed well during a two year trial.

MacHarg J. P.
a) 'MANUFACTURER'S CASE HISTORY - Exchanger Tests Verify 2.0 kWh/m3 SWRO Energy Use'. Available at http://www.energyrecovery.com/UserFiles/file/archives/news/pdf/PressureExchangeSWRO.pdf [Last viewed on 7 August 2011].
b) 'SWRO Energy Recovery Technology Shatters Design Barriers'. Available at http://ocean-pacific-tec.com/imagenes/news/17%20Technology%20Shatters%20Design%20Barriers.pdf [Last viewed on 7 August 2011]. This document quotes a range of 1.72- 1.87 kWh/m^3 between 18 and 25 degrees C.

Markvart T. 2002. 'Photovoltaic Solar Energy Conversion' University of Southampton. European Summer University: Energy for Europe Strasbourg, 7-14 July 2002 available at http://www.soton.ac.uk/~solar/files/Strasbourg.pdf [Last viewed on 7 August 2011].

Mearns E. November 2007. 'The World's Expected Carrying Capacity in a Post-Industrial Agrarian Society'. Available at http://www.theoildrum.com/node/3090. [Last viewed on 7 August 2011].

Minesto. 2012. 'Deep Green Technology'. Minesto website page. Available at http://www.minesto.com/deepgreentechnology/index.html [Last viewed on 1 September 2012].

Minn M. May 2009. 'Energy Use In American Food Production'. Available at http://www.pulsecanada.com/uploads/8c/96/8c966601850c2c80ccdd00081c0560fb/2009-05-11-Minn-Energy-Use-in-American-Food-Production.pdf [Last viewed on 7 August 2011].

Munich Re Foundation. 2011. 'Second Phase of the Project. Munich Re Foundation Website. Available at v http://www.munichre-foundation.org/home/Projects/Water/Eritrea_ProjectVisit/Eritrea_ProjectVisit_Phase2.html [Last viewed on 7 August 2011].

Nardin R. July 2003. 'Newhaven Desalination Appraisal (for South East Water)'. Dynamco Ltd.
a) Page 36. Cost of Sea Water Treatment – Capital Costs.
b) Page 37. Cost of Sea Water Treatment – SWRO Annual Operating Costs.

Natural Capitalism Solutions. 2010. 'Coal Plants in Transition'. available at http://www.natcapsolutions.org/CoalPlantsinTransition.pdf [Last viewed on 7 August 2011].

NowPublic.com: Worldwide water shortages by 2080. NowPublic News Coverage http://www.nowpublic.com/environment/worldwide-water-shortages-2080#ixzz1Tn3MRcgG [Last viewed on 7 August 2011].

Pearce F. 2006. When the rivers run dry' published by Eden Project Books. Synopsis presented in The New Scientist 25 February 2006 page 32 'The parched planet'.

Parry M.L., Canziani O. FPalutikof J. P., van der Linden P. J. and C.E. Hanson C. E. 2007. IPPC: Summary for Policymakers. In: Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Eds., Cambridge University Press, Cambridge, UK. Available at http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf [Last viewed on 7 August 2011].

PB (Parsons Brinkerhoff) March 2004. 'The Cost of Generating Electricity - A study carried out by PB Power for The Royal Academy of Engineering'. ISBN 1-903496-11-X March 2004. Available at http://www.raeng.org.uk/news/publications/list/reports/Cost_of_Generating_Electricity.pdf [Last viewed on 7 August 2011].
a) See Page 43. Appendix A. Section A.6.1 Onshore. Table A.15 – Onshore Wind Farm Characteristics'.
b) See Page 45. Appendix A. Section A.6.2 Offshore. Table A.17 – Offshore Wind Farm Characteristics'.

PB (Parsons Brinkerhoff). December 2009. 'Powering the Future, Full Report - Mapping our low-carbon path to 2050'. Available at http://www.pbpoweringthefuture.com/ [Last viewed on 7 August 2011].

Pelamis Wave Power. 2011. 'CEO at Agucadoura'. Pelamis wave power website Available at http://www.pelamiswave.com/our-projects/project/6/CEO-at-Agucadoura [Last viewed on 7 August 2011].

Philibert C. 2010. 'Technology Roadmap - Concentrating Solar Power', IEA International Energy Agency. Available at http://www.iea.org/papers/2010/csp_roadmap.pdf [Last viewed on 7 August 2011].

POST (Parliamentary Office of Science and Technology). December 2005. 'Cleaner Coal' Postnote. Number 253. Available at http://www.parliament.uk/documents/post/postpn253.pdf [Last viewed on 7 August 2011].

Power Engineering. March 2010. 'IGCC Cost Wrap'. Power Engineering Webpage. Available at http://www.powergenworldwide.com/index/display/articledisplay.articles.powergenworldwide.coal-generation.new-projects.2010.03.igcc-cost-wrap.QP129867.dcmp=rss.page=1.html [Last viewed on 7 August 2011].

Previsic M. June 2006. 'System Level Design, Performance, Cost and Economic Assessment – San Francisco Tidal In-Stream Power Plant'. EPRI (Electric Power Research Institute Inc). Available at http://oceanenergy.epri.com/attachments/streamenergy/reports/006_CA_06-10_-06.pdf [Last viewed on 7 August 2011].

PRODES. 2010. 'Existing_plants_web_version-3.xls'. ProDes project results available at http://www.prodes-project.org/index.php@id=105.html. [Last viewed on 7 August 2011].

PwC. 2010. '100% renewable electricity. A roadmap to 2050 for Europe and North Africa'. Price Waterhouse Coopers, in collaboration with researchers from the Potsdam Institute for Climate Impact Research (PIK), the International Institute for Applied Systems Analysis (IIASA) and the European Climate Forum (ECF) available at http://www.pwc.co.uk/eng/publications/100_percent_renewable_electricity.html [Last viewed on 7 August 2011].

REN21. 2010. 'Renewables 2010 Global Status Report (Paris: REN21 Secretariat)'. Available at http://www.ren21.net/Portals/97/documents/GSR/REN21_GSR_2010_full_revised%20Sept2010.pdf [Last viewed on 7 August 2011].

REN21. 2011. 'Renewables 2011 Global Status Report (Paris: REN21 Secretariat)'. Available at http://www.ren21.net/Portals/97/documents/GSR/REN21_GSR2011.pdf [Last viewed on 7 August 2011].

Renewable UK. 2011. 'Marine Renewable Energy'. Renewable UK website, quote available at http://www.bwea.com/marine/resource.html [Last viewed on 7 August 2011].

Rheinlander J. 2007. 'De-central Water and Power Supply Integrating Renewable Energy – Technical and Economic Performance Prediction'. Center for Solar Energy and Hydrogen Research Baden-Wurttemberg, Germany. Published by Springer. Available at http://books.google.co.uk/books?id=iA75bZKcilYC&pg=PA348&lpg=PA348&dq=intermittent+operation+of+ro+plant&source=bl&ots=CK_s-CRvyO&sig=gDp5Pilzgr8CXXNUVBu0ClbPJ2o&hl=en&sa=X&ei=wRCLT-DBKTC0QWzxcW5CQ&ved=0CFgQ6AEwBA#v=onepage&q=intermittent%20operation%20of%20ro%20plant&f=false [Last viewed 7 August 2011].

Rubbelke D. T.G., and Rive N. December 2008. 'Effects of the CDM on Poverty Eradication and Global Climate Protection'. Centre for International Climate and Environmental Research Oslo (CICERO). Available at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1314207 [Last viewed 7 April 2012].

Rybar S. Vodnar M., Vartolomei, F. L., Méndez R. L., Ruano J. B. L. 2005. 'Experience with Renewable Energy Source and SWRO Desalination in Gran Canaria'. Presented at the International Desalination Association World Congress: SP05-100. Available at http://www.membranes.com/docs/papers/New%20Folder/Soslaires%20Canarias%20Desalination%20Plant.pdf [Last viewed on 7 August 2011].

Schneider B. 2005. 'Selection, operation and control of a work exchanger energy recovery system based on the Singapore Project' – Desalination 184 (2005) 1177 – 1190 achieved 2.01kWh/m^3.

Schneider L. November 2007. 'Is the CDM fulfilling its environmental and sustainable development objectives? An evaluation of the CDM and options for improvement'. Available at http://www3.oeko.de/oekodoc/622/2007-162-en.pdf [Last viewed 7 April 2012].

SEEDA (South East England Development Agency). May 2007. 'Atlas of the Tidal Energy Resource on the South East Coast of England', prepared by Marine and Technical Marketing Consultants (MTMC). Available at http://www.solentoceanenergy.com/Seeda_final5.pdf [Last viewed on 7 August 2011].

Self Help Africa' website page http://www.selfhelpafrica.org/selfhelp/main/NEWS-ERI-one.htm . [Last viewed on 7 August 2011] provides greater detail of rain water harvesting and other water capture initiatives being undertaken.

Sharp. 2009. Sharp solar electricity 235W Solar Panel, Monocrystalline, Clear, NU-U235F1 datasheet available at http://www.pvpower.com/pdf/datasheets/sharp/pv%20modules/235spec.pdf [Last viewed on 7 August 2011].

Shipley A.M., Elliot R.N. 2004. 'Stationary fuel cells – future promise, current hype'. Report IE041, American Council for an Energy-Efficient Economy.

Sims C. November 2006. 'Garden watering restrictions: A review of hosepipe ban legislation'. Waterwise for Defra. Available at http://www.waterwise.org.uk/data/2006_Waterwise_hosepipe_bans.pdf [Last viewed on 7 August 2011].

Stover R., Cameron I. 2007. 'Energy recovery in Caribbean seawater reverse osmosis'. Presented to the WEB Aruba N.V. International Desalination Conference 2007 and available at http://www.slc.ca.gov/Reports/Carlsbad_Desalinization_Plant_Response/May_response/Appendix%20D%20Energy%20Recov%20in%20Caribbean%20Sea%20RO.pdf [Last viewed on 7 August 2011].

Stover R. October 2009. Energy Recovery Devices Help Lower Cost of RO Desalination. Available at http://www.waterworld.com/articles/mem/articles/print/volume-2/issue-30/Features/energy-recovery-devices.html [Last viewed on 7 August 2011].

Soerensen H. C. October 2006. 'Wave Dragon – from the 20kW to the 7MW prototype device'. Presentation by Project Coordinator for Wave Dragon and based on a wave climate of 24kW/m (which incidentally was the least powerful wave climate option available). Available at http://ec.europa.eu/research/energy/pdf/gp/gp_events/ocean_energy/1010_wave_dragon_en.pdf [Last viewed on 7 August 2011].

Stern N. 2007. 'The Economics of Climate Change. The Stern Review'. ISBN: 9780521700801. Available at http://www.webcitation.org/5nCeyEYJr [Last viewed on 7 August 2011].

Strahan D. 2008. 'The great coal hole' New Scientist (19 January 2008)

Strahan D. 2009. 'Scraping the bottom of the barrel'. New Scientist (5 December 2009).

Swiss-RE. December 2010. 'Swiss Re – its history and Sharing Solutions programme'. Available at http://www.wateraid.org/documents/swissre.pdf [Last viewed on 7 August 2011].

Tekle G., Ogbal E. 2008. 'Eritrea: National and City Urban profile – Asmara, Massawa and Mendefera' prepared as part of the United Nations Settlement Programme 2008 available at http://www.google.co.uk/url?sa=t&source=web&cd=1&ved=0CBsQFjAA&url=http%3A%2F%2Fwww.unhabitat.org%2Fpmss%2FgetElectronicVersion.asp%3Fnr%3D2718%26alt%3D1&rct=j&q=Eritrea%3A%20National%20and%20City%20Urban%20profile%20-%20Asmara%2C%20Massawa%20and%20Mendefera&ei=s-gFTqOBClew0QWdj_UL&usg=AFQjCNF_rRuWNOhj_EVu5pYUbjsLwKoClw [Last viewed on 7 August 2011].

Thames water. 2010. 'New water works taps tidal Thames', available at http://www.thameswater.co.uk/cps/rde/xchg/corp/hs.xsl/10279.htm [Last viewed on 7 August 2011].

The Wind Power. 2011. The Wind Power wind turbines and wind farm data base webpage available at http://www.thewindpower.net/index.php [Last viewed on 7 August 2011].

Thomson A. M. 2003 'Reverse-Osmosis Desalination of Seawater Powered by Photovoltaics Without Batteries'. Available at http://www-staff.lboro.ac.uk/~elmt/Murray%20Thomson%20Thesis.pdf [Last viewed on 7 August 2011].

a) Monthly irradiance averages at Massawa taken directly from page 95
b) The Massawa mid-temperature equation was taken directly from page110.

Thornton J. September 2005. 'The Water Book: find it, move it, store it, clean it... use it'. Cat Publications (2005) ISBN 1-90217 -523-9 - Data courtesy of the Environment Agency and the Building Research Establishment.

Thwaites T. February 2007. 'A bank for wind power'. The New Scientist. Issue 2586.

ULCOS. 'Alkaline Electrolysis' web page 'Ultra–Low Carbon dioxide (CO_2) Steelmaking (ULCOS)'. Available at http://www.ulcos.org/en/research/electrolysis.php [Last viewed on 7 August 2011].

UNEP. July 2011. 'The Rush for Land and Its Potential Environmental Consequence'. UNEP Global Environmental Alert Service (GEAS). Available at http://na.unep.net/geas/archive/pdfs/Jul_11_Land_Rush.pdf [Last viewed on 7 August 2011].

UNESCO 'Chapter 8. Securing food for a growing population'. United Nations World Water Development Report. Available at http://www.unesco.org/water/wwap/wwdr/pdf/chap8.pdf [Last viewed on 7 August 2011].

UNFCCC (United Nations Framework Convention on Climate Change). December 2001. 'THE STATE OF ERITREA from The Ministry of Land, Water and Environment, ERITREA'S INITIAL NATIONAL COMMUNICATION'. Available at http://unfccc.int/resource/docs/natc/erinc1.pdf [Last viewed on 7 August 2011].

UNICEF (United Nation's Children's Fund). April 2012. 'Response to the Horn of Africa Emergency. A continuing crisis threatens hard-won gains' Regional six-month Progress Report'. Available at http://www.unicefusa.org/assets/pdf/Horn-of-Africa-Six-Month-Report-April-2012.pdf [Last viewed on 19 July 2012].

Vaughan A. July 2012. 'Solar companies demand £2.2m in damages after feed-in tariff cuts'. The Guardian. Available at http://www.guardian.co.uk/environment/2012/jul/13/solar-damages-feed-in-tariff-cuts?newsfeed=true [Last viewed 13 July 2012]

Wagner A. January 2011. 'International Fuel Prices 2010 / 2011. Data Preview – January 2011'. GIZ (The Deutsche Gesellschaft für Internationale Zusammenarbeit) GmbH. Available at http://www.gtz.de/de/dokumente/giz2011-international-fuel-prices-2010-2011-data-preview.pdf [Last viewed on 7 August 2011].

UNIDO (United Nations Industrial Development Organization) January 2008. 'Promoting cleaner industry for everyone's benefit'. Collaborating agencies: WHO (World Health Organization)/ UNDESA (United Nations Department of Economic and Social Affairs). Available at http://www.scribd.com/doc/8065685/Chap-9 [Last viewed on 7 August 2011].

US DoE (US Department of Energy). May 2007. 'Pumping systems Tip Sheet 2. Control strategies for centrifugal pumps with variable flowrate requirements' DOE/GO-102007-2230, available at http://www1.eere.energy.gov/industry/bestpractices/pdfs/38949.pdf [Last viewed on 7 August 2011].

WBCSD (The World Business Council for Sustainable Development). August 2009. Facts and Trends – Water Version 2 ISBN 2-940240-70-1community (2009). Available at http://www.wbcsd.org/DocRoot/ID1tMGiLZ7NL9mBOL2aQ/WaterFactsAndTrends-Update.pdf [Last viewed on 7 August 2011].

WHO. June 2004 "Health Aspects of Air Pollution. Results from the WWWHO Project "Systematic Review of Health Aspects of Air Pollution in Europe". Available at http://www.euro.who.int/ data/assets/pdf file/0003/74730/E83080.pdf [Last viewed on 7 August 2011].

WHO/UNICEF Joint Monitoring Programme. Available at http://www.wssinfo.org/data-estimates/introduction/ [Last viewed on 7 August 2011].

WHO/UNICEF (The World Health Organization/United Nations Children's Fund). 2000. 'Global Water Supply and Sanitation Assessment 2000 Report'. Available at http://www.who.int/water sanitation health/monitoring/globalassess/en/ [Last viewed on 7 August 2011].

WHO/UNICEF (The World Health Organization/United Nations Children's Fund). 2002. 'Basic Needs and Right to Health'. Available at http://www.unesco.org/water/wwap/wwdr/pdf/chap5.pdf [Last viewed on 7 August 2011].

Wilson P. January 2011. Based on e-mail correspondence on '14 Jan 2011' with Paul of Parsons Brinkerhoff author of 'Powering the Nation'. Available at http://www.pbpoweringthefuture.com/ [Last viewed on 7 August 2011].

Wind Site Evaluation. 'How to estimate the Electricity Production of a Wind Farm'. See 'Shape Factor'. Wind evaluation website available at http://www.wse.ie/estimate-electricity-production-wind-farm.php [Last viewed on 7 August 2011].

Worldwide Movers. 2001. 'Eritrea. Congratulations and Welcome'. Available at http://www.worldwidemoversafrica.com/Eritrea/index-eritrea.htm#wat [Last viewed on 7 August 2011].

Worley Parsons. 2009. 'Strategic Analysis of the Global Status of Carbon Capture and Storage Report 2: Economic assessment of carbon capture and storage technologies, Final Report ©, 2009 Global CCS Institute. Produced by Worley Parsons and available at http://cdn.globalccsinstitute.com/sites/default/files/publications/5751/report-2-economic-assessment-carbon-capture-and-storage-technologies.pdf [Last viewed on 7 August 2011].

Zoulias E. I., with Lymberopoulos N. 2008. 'Hydrogen-based autonomous power systems: techno-economic analysis of the integration of Hydrogen in Autonomous Power Systems'. Available to read online at http://www.springer.com/engineering/energy+technology/book/978-1-84800-246-3 [Last viewed on 7 August 2011].

Appendix A

This Appendix discusses the following with respect to their potential impact on the already limited reusable water supplies:

- Environmental Legislation
- Global Disparity of water supplies
- The potential impacts of global warming, and
- The future requirements for water.

1 Environmental Legislation

Various European environmental directives place a limitation on the water that can be legally abstracted. These include the Habitats Directive [European Economic Commission, 1992], the Water Framework Directive[1] [European Economic Commission, 1992], and in the UK there are programmes to maintain Sites of Special Scientific Interest (SSSIs), Sites of Nature Conservation Importance (SNCIs), and Biodiversity Action Plans (BAP).

Many of these programmes put pressure on UK Water companies to reduce existing abstraction regimes.

2 Global Disparity

Figure 1 below, which was taken from 'Water for People, Water for Life' [UNESCO, 2003a p9] presents the global overview of water availability versus the population which identifies the continental disparities, and in particular the pressure put on the Asian continent, which supports more than half the world's population with only 36 percent of the world's fresh water resources available to it.

[1] The Water Framework Directive establishes a framework for Community Action in the field of water policy and has a number of objectives, such as preventing and reducing pollution, promoting sustainable water usage, environmental protection, improving aquatic ecosystems, and mitigating the effects of floods and droughts. Its ultimate objective is to achieve "good ecological and chemical status" for all Community waters by 2015.

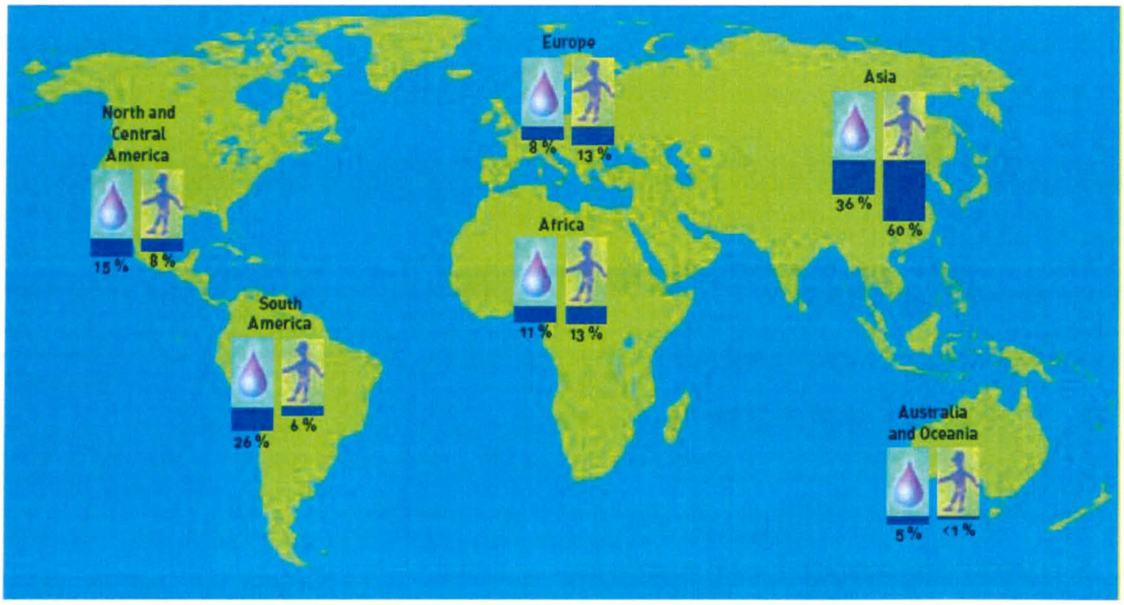

Figure 1: Water availability versus population

Figure 2 below, which was based on 'Global water supply and sanitation assessment 2000' [WHO/ UNICEF, 2000] indicates (with its red highlights) that the infrastructure to supply the available water directly to the user is a limitation in itself, and is currently most acute in East Africa and the countries bordering the Caspian Sea[2].

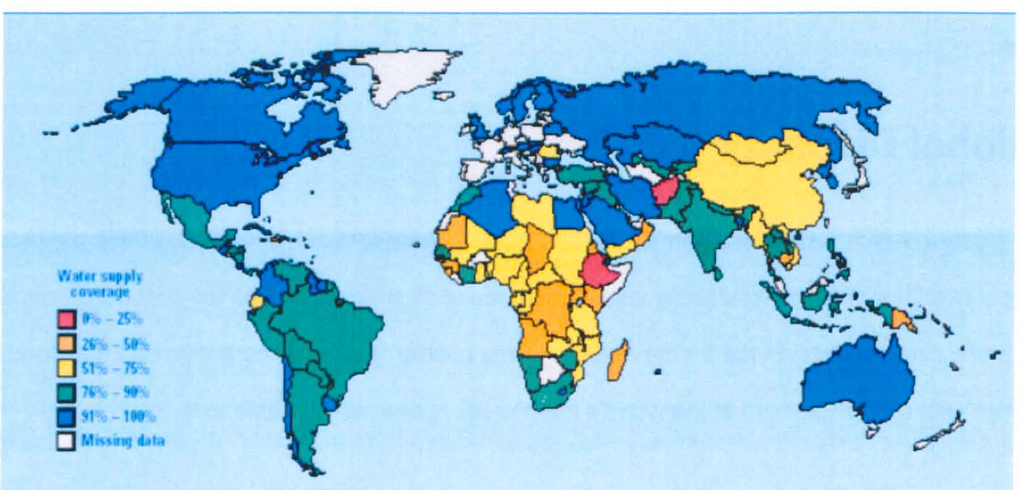

Figure 2: Water supply coverage in 2000 (percentage of inhabitants served by adequate water supply)

The disparity between supplies of renewable water supply is in some cases particularly localised, as shown by the example of the South East of England receiving less rainfall per person than in the Sudan [Harrison, 2004].

---

[2] These countries include Iran, Kazakhstan, Turkmenistan, Uzbekistan and Afghanistan.

Figure 3 below shows the disparity of South East England in comparison to the rest of the British Isles, in January 2006.

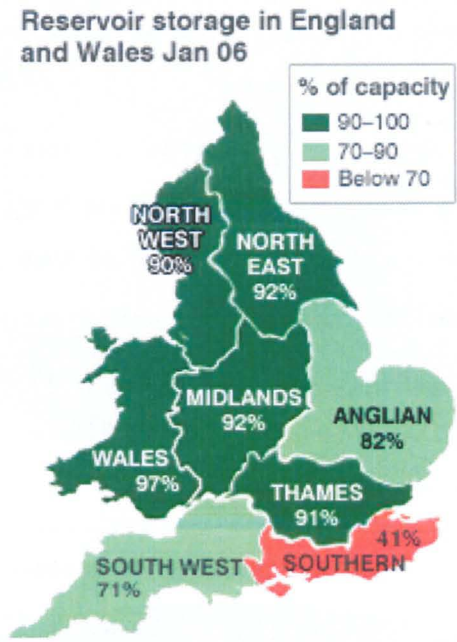

Figure 3: Comparison of England and Wales

3 Impacts of Global Warming

A further limitation is placed on available water resources by the direct and indirect impacts of Global Warming and Climate Change.

3.1 Direct impacts

The precise impact of climate change on water resources is uncertain, with precipitation and river flows increasing overall, but with some areas experiencing a decrease and others an increase. The precipitation will probably increase from latitudes 30°N and 30°S, but many tropical and sub-tropical regions will probably receive lower and more erratic rainfall.

Stream flows at low-flow periods may well decrease, and water quality will undoubtedly worsen, because of increased pollution loads and concentrations, and higher water temperatures.

By the middle of this century, it is estimated by UNESCO [UNESCO, 2003b p10] that climate change will account for about 20 percent of the increase in global water scarcity[3] , within the following bounds:

- At best 2 billion people in forty-eight countries, and

[3] According to UNEP's definition, when an area's annual water supply drops below 1,000 m^3 per person, the population faces water scarcity.

- At worst 7 billion people in sixty countries will be water-scarce.

3.2 Indirect impacts

A significant aspect of global warming and climate change with an indirect impact on water availability, is the incidence of natural disasters.

Between 1991 and 2000 [UNESCO, 2003c, p23], the number of people affected by natural disasters rose from 147 million per year to 211 million per year (an increase of nearly 45%), and the observational evidence of two studies published in 2005, [Emmanual, 2005] and [Webster et al, 2005] shows that the intensity of tropical storms has increased over the past 30 years. In particular, the strongest categories of hurricane[4] (four and five), have doubled in frequency, while the number of weaker hurricanes has decreased. Between 1991 and 2000, more than 665,000 people died in 2,557 natural disasters, of which almost 90 percent (around 2200) were water-related.

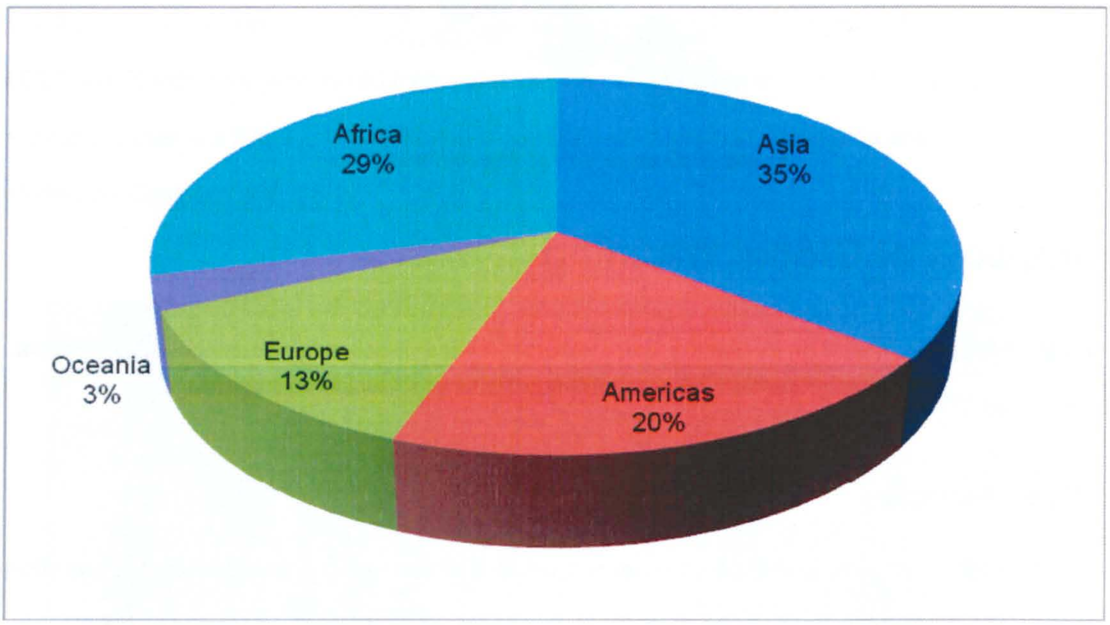

Figure 4: Distribution of water-related natural disasters (1990 – 2001)

The continents most affected by these disasters were Asia and Africa, as illustrated in Figure 4 above. It is also noteworthy that according to 'The Quality and Accuracy of Disaster Data: A comparative analysis of three global data sets' [Guha-Sapir and Below, 2002], the accuracy of disaster data would benefit from standardisation.

Figure 5 below presents the water-related disasters between 1990 and 2001, based on the categorised by type.

---

[4] Based on the Saffir-Simpson Hurricane Scale

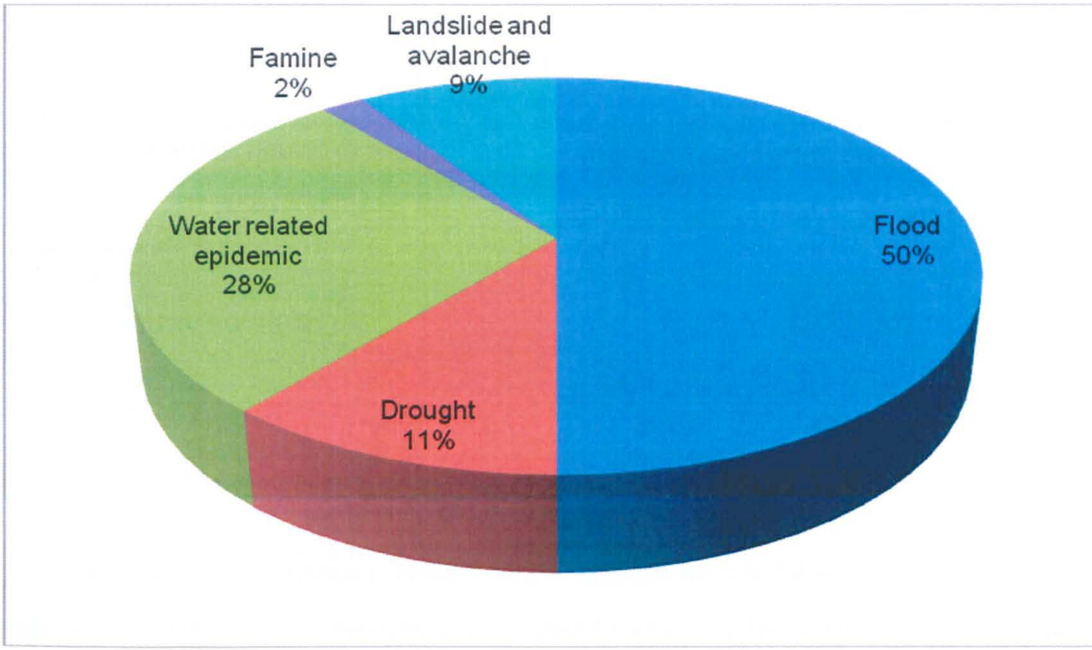

Figure 5: Types of water-related natural disasters, 1990–2001.

According to the 'Water for People, Water for Life' [UNESCO, 2003d, p23], of these water-related disasters:

- Floods represented about 50 percent, and caused 15% of all deaths in natural disasters
- Water-borne and vector-borne diseases accounted for about 28 percent of deaths, and
- Droughts 11 percent, but accounted for 42% of all deaths in natural disasters.

Floods and droughts due to extreme weather will almost undoubtedly undermine the available water supply, especially where the supply infrastructure is not robust, making their occurrence in the developing world disproportionately lethal.

It is particularly noteworthy that some 97 percent of all natural disaster deaths occurred in developing countries.

4 The future for global water usage

The future outlook for global water usage, according to 'Science on Sustainability – 2006' [RSBS, 2006] is shown below in Figure 6, based on trillions of cubic metres of water used.

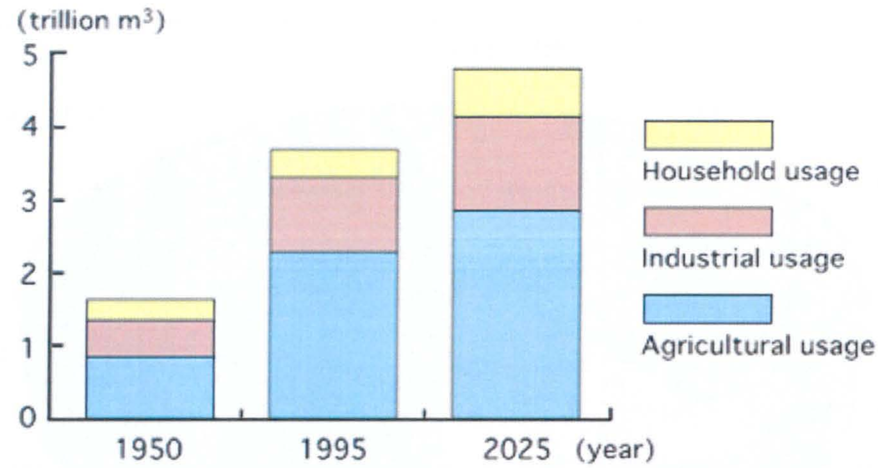

Figure 6: Future outlook for global water usage

The greatest concern for the future is not so much that there will be a sudden large-scale water shortage, but that the demand for fresh water will continue to grow, causing an increase in the number of countries and regions facing water stress and constant water scarcity.

Almost 800 million people in developing countries are currently undernourished and the International Development target of halving this figure [European Council, 2002] by 2015 will not be met before at least 2030 [FAO, 2003].

According to the World Water Council [World Water Council], the global population has tripled in the 20th century, but water usage increased by a factor of six. There is growing concern that four billion people (or as much as 50% of world population in 2025) globally may face water stress. Under particular stress are key regions in Africa, China, India, the Middle East, Europe, Australia, and North America, including the western part of the United States, as illustrated below in Figure 7.

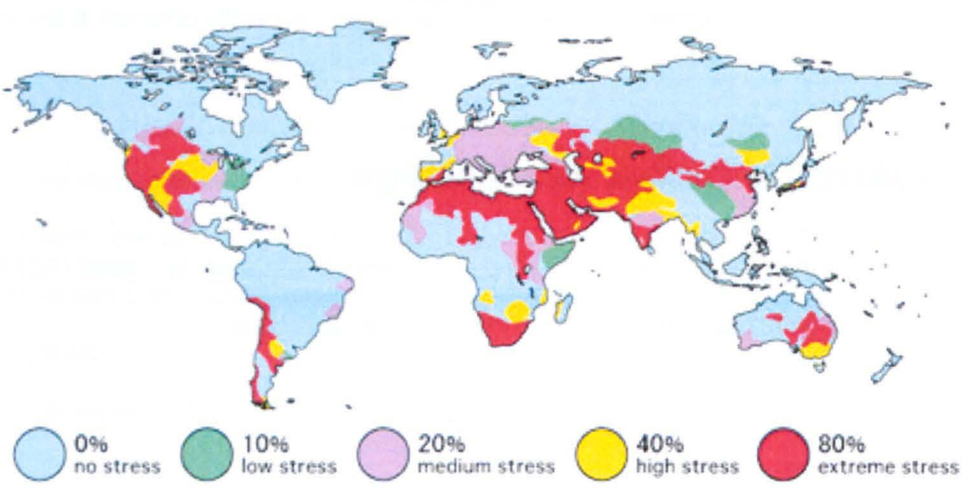

Figure 7: 2025 World 'water stress' status quo scenario

It can therefore be seen how intimately the growth of future food production is tied to a stable water supply.

5 References

European Council. 2002. Communication from the Commission to the European Parliament, The Council, the Economic and Social Committee of the Regions. Brussels, 13.2.2002 COM 82 Final. Available at http://eur-lex.europa.eu/LexUriServ/site/en/com/2002/com2002_0082en01.pdf [Last viewed on 7 August 2011].

European Economic Commission. 21 May 1992. Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora (The Habitats Directive). Available at http://europa.eu/legislation_summaries/environment/nature_and_biodiversity/l28076_en.htm. [Last viewed on 7 August 2011].

European Economic Commission. 23 October 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community Action in the field of water policy. Available at http://ec.europa.eu/environment/water/water-framework/index_en.html

FAO (Food and Agriculture Organisation). 2003. '2.2.3 Food Security outcomes'. Available at http://www.fao.org/docrep/005/y4252e/y4252e04a.htm [Last viewed on 7 August 2011].

Guha-Sapir D., Below R. 2002. 'The Quality and Accuracy of Disaster Data: A comparative analysis of three global data sets'. Centre for Research on Epidemiology of Disasters (CRED). Available at http://www.cred.be/sites/default/files/Quality_accuracy_disaster_data.pdf) [Last viewed on 7 August 2011].

Harrison D. 13 June 2004. The Daily Telegraph. Available at http://www.telegraph.co.uk/news/uknews/1464400/Its-official-the-South-East-has-less-water-per-head-than-Sudan.html [Last viewed on 7 August 2011].

RSBS (Research on the Scientific Basis for Sustainability). 2006. 'Science on Sustainability 2006 – Summary Report. A view from Japan' Available at http://www.sos2006.jp/english/rsbs_summary_e/ScienceOnSustainability2006.pdf [Last viewed on 7 August 2011].

UNESCO. 2003. The Executive Summary of the United Nations world water development report – Water for people – water for life'. Available at http://unesdoc.unesco.org/images/0012/001295/129556e.pdf [Last viewed on 7 August 2011].

a) Diagram taken from page 9.
b) Water scarcity estimation provided on page 10.
c) Water related natural disasters discussed on page 23.
d) Water related natural disasters discussed on page 23.

Webster P.J., Holland G.J., Curry J.A. and H-R. Chang. 2005. 'Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment'. Science, 309, 1844-1846. Available at http://www.sciencemag.org/content/309/5742/1844.full.pdf [Last viewed on 7 August 2011].

WHO/ UNICEF. 2000. Global Water Supply and Sanitation Assessment 2000 Report. Available at http://www.who.int/water_sanitation_health/monitoring/jmp2000.pdf [Last viewed on 7 August 2011].

World Water Council. 2010. World Water Council web page. Available at http://www.worldwatercouncil.org/index.php?id=25 [Last viewed on 7 August 2011].

Appendix B

Introduction

This Appendix describes how the data for the six-stage modelling exercise (Figure 1) for this research, was derived.

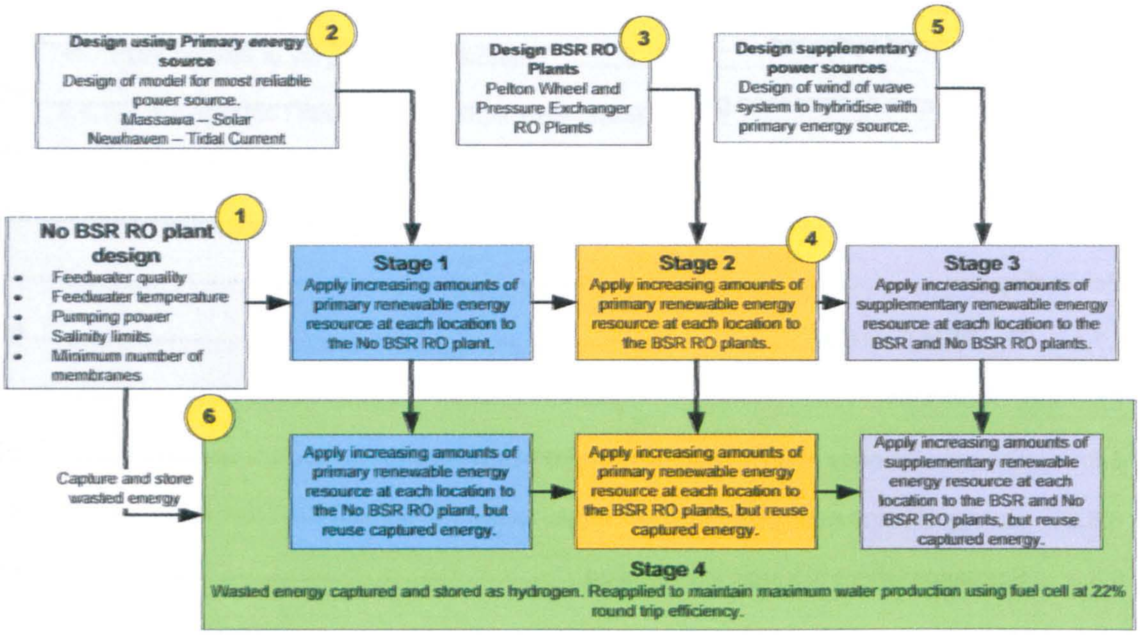

Figure 1: Modelling Process Overview.

The modelling stages were:

1. No BSR RO Plant Design
2. Model of primary renewable energy source, and its application to No BSR RO Plant
3. Design of BSR RO plants
4. The application of primary renewable energy source to BSR RO plants
5. Design of supplementary renewable energy sources and application to BSR and No BSR RO Plants, and
6. Design of model for hydrogen storage and re-use.

These stages are shown below in Figure 2 in relation to the modelling for the No RO plant.

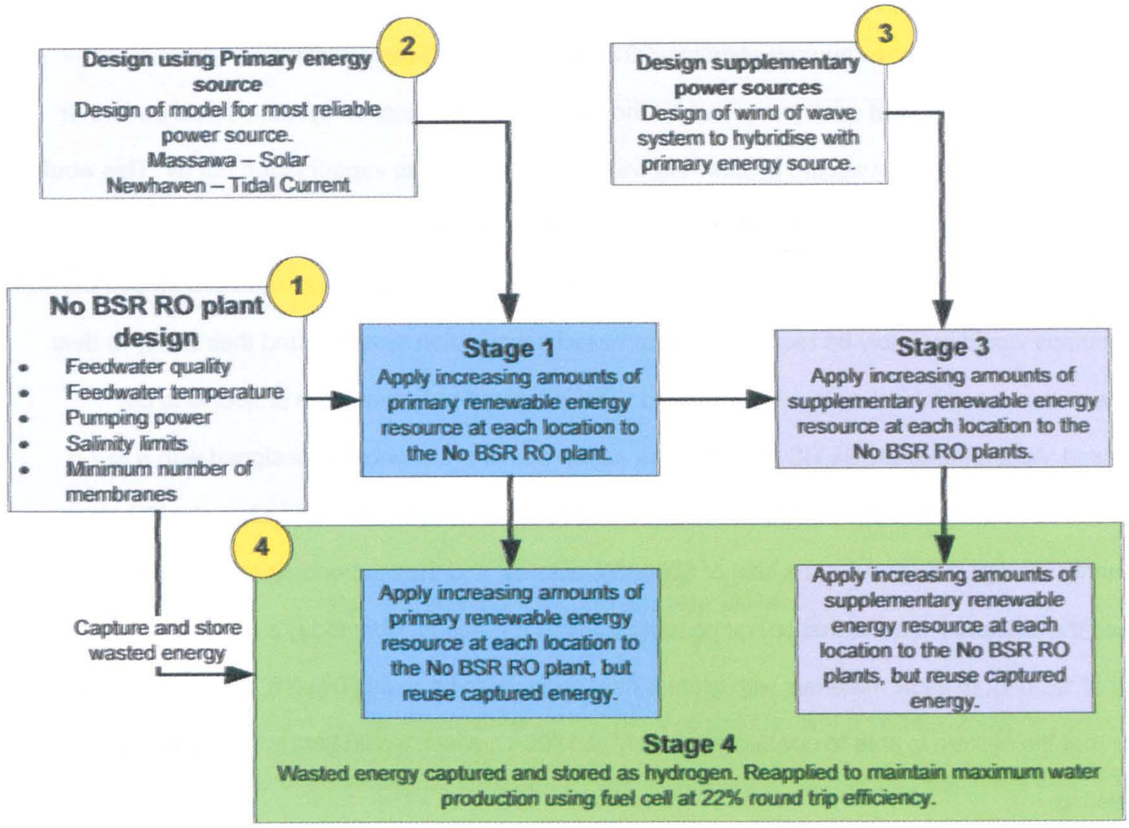

Figure 2: No BSR RO Plant modelling

1. Desalination Plant Selection

For the purpose of this research, the desalination plant selected was reverse osmosis due to having the lowest specific power consumption. In reality, as detailed in 'Renewable Energy Opportunities in Water Desalination' [Al-Karaghouli and Kasmerski], the selection of the appropriate renewable energy desalination technology depends on a number of factors, including plant size, feed-water salinity, remoteness, availability of grid electricity, technical infrastructure, and the type and potential of the local renewable energy resources available locally. Proper matching of standalone power-supply desalination systems has been recognised as being crucial if the system is to provide a satisfactory supply of power and water at a reasonable cost. If this decision making process were employed it is possible that other methods of desalination, especially when coupled to the most prevalent local energy sources, would have been selected.

- Massawa – Heat based mechanically driven RO [Manolakos et al, 2007] or flash evaporation desalination with direct use of renewable generated heat (solar thermal, geothermal, concentrated solar power with molten salt for heat storage, etc))

- Newhaven – perhaps would have retained RO, but used direct mechanical pressurisation such as the SeaDog wave pump [LaMonica, 2010] or the oyster [Folley, 2007][1].

It is noteworthy that the heat quality required for the heat based desalination systems could be further improved by increasing the vacuum to allow the water to evaporate into vapour laden hot air. This would also tend to improve the conversion systems' susceptibility to power outages.

Although, in the absence of a dedicated electrical power supply to operate water and vacuum pumps, steam pumps would probably be required for heat based desalination systems, and their ability to deal with intermittent power/ heating input would need to be investigated further if the project is to be progressed. According to EU SETIS [SETIS] solar power plants are now being designed with 6 to 7.5 hours of full-load storage, which would be enough to allow almost continuous operation of a RO plant. The energy storage though was at a cost of \$500/kW installed and the methodologies proposed to increase the efficiency require that operating temperatures are raised, from today's sub 600ºC to in excess of 1200ºC, to allow materials with greater heat capacity to be used [Trabish, 2012]. This would require that the system is able to operate effectively at 1200ºC, which would probably require significant engineering.

1.1 The No BSR RO Plant

Reverse osmosis (RO) is a form of filtration, in which the filter is a semi-permeable membrane that allows water to pass through, but not salt. When a membrane of this type has saltwater on one side and freshwater on the other, and no other forces are acting, water will flow through the membrane towards the saltwater side, reducing the difference in salt concentration. This is the natural process of osmosis, which is widely employed in the cells of all living species. In reverse osmosis desalination, the aim is to increase the quantity of freshwater, and so a pump is employed to make the flow reverse, hence the name: reverse osmosis.

The osmotic pressure of typical seawater is around 26 bar, and this is the pressure that must be overcome in order to reverse the natural osmotic flow. Twenty-six bar also equates to the ambitious theoretical minimum energy consumption of 0.7 kWh/m^3, but in practice, a significantly higher pressure is used in order to achieve a generous flow of freshwater [Lachish, 2003], known as the 'permeate'.

As freshwater passes through the membrane, the remaining saltwater becomes more concentrated and, for the process to continue, this concentrate, known as the brine, must be continuously replaced by new

[1] The wave resource at Newhaven is relatively low, as explained in section 5.4.3.1 'Wave height' on page B49, which would tend to limit the viability of any wave powered device at that location.

feed water. To achieve this, the feed water is pumped across the membrane as well as through it; hence, RO is a cross-flow filtration process as depicted in Figure 3 below.

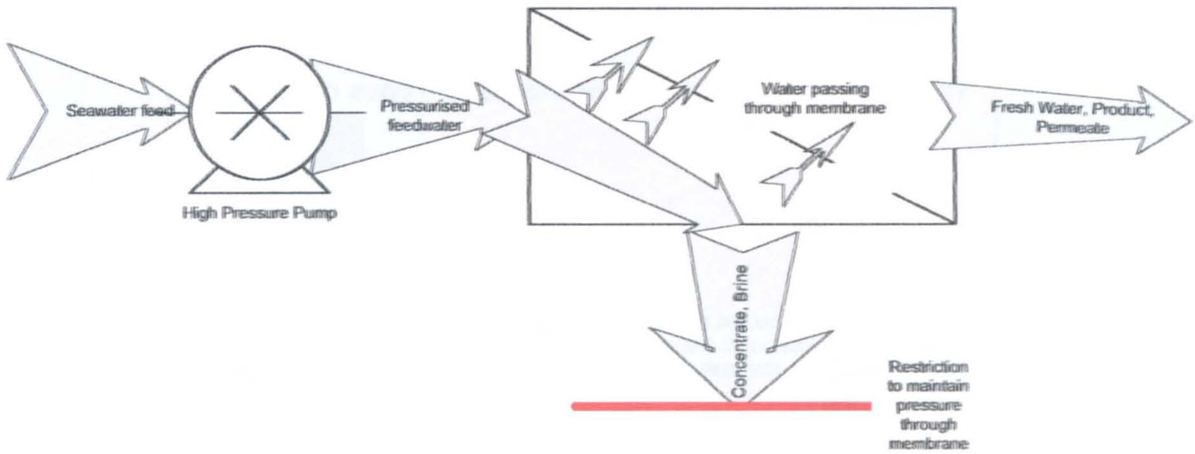

Figure 3: Reverse Osmosis filtration process

As can be seen from Figure 3 above, a proportion of the pressurised feedwater comes out of the reverse osmosis module as waste or concentrate. This concentrate is at a pressure only slightly below that of the feedwater, meaning that it contains a significant amount of the hydraulic power originally supplied by the pump.

In larger RO systems, this energy can be partially recovered, dramatically improving the overall system efficiency. This is known as brine-stream recovery (BSR) and is described in more detail in section 3.2 and section 3.3 for the Pelton Wheel and Pressure Exchanger variants, respectively[2].

To model the No BSR RO plant, it was necessary to define the following:

- Operational characteristics of the RO plant
- Feedwater temperatures
- Water required from the RO plant.

1.2 Operational characteristics of the RO plant

The commercially-available options (from *Dow Industries*) investigated for the membrane to employ for this research, which would define the operating characteristics of the RO plant, were as follows:

- SW30XLE-400i
- SW30HR-380, and
- SW30HR-320.

[2] In smaller RO systems, brine-stream energy recovery is often omitted, which reduces capital costs but adds considerably to running costs (in particular, energy use).

Figure 4 below indicates the suitability of the various membranes to different levels of feedwater quality, (where 'beachwell or siting offshore' represents a cleaner feedwater source than the 'open intake'), for various RO plant configurations.

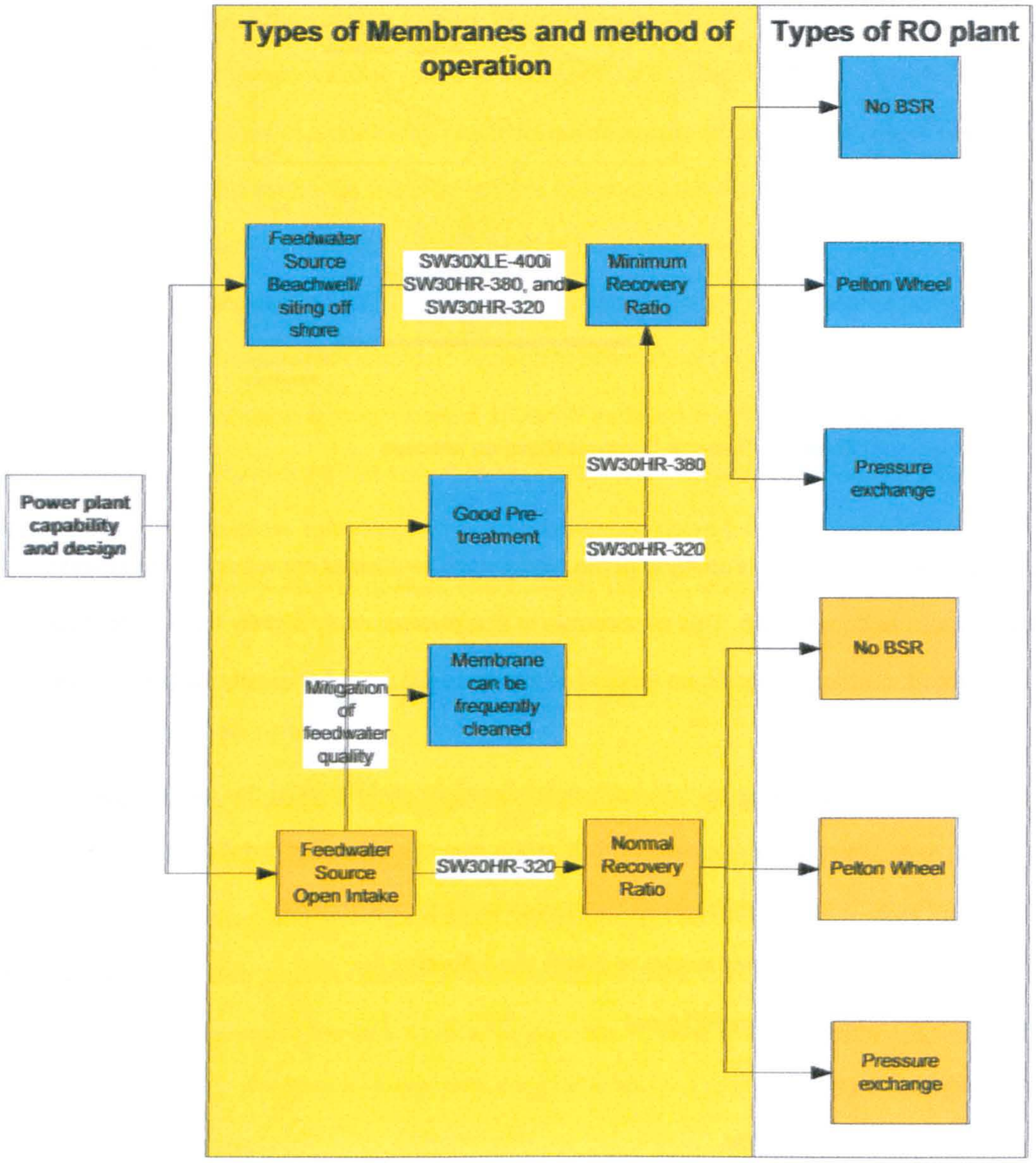

Figure 4: Types of membranes and their modes of operation.

The SW30HR-320 was selected from the options available as (although not the best option in terms of water production efficiency), it was the most versatile and robust in operation, in that it could be used with both untreated and pre-treated feedwater at a range of recovery ratios[3] with all the types of RO plant expected to be modelled within this thesis.

[3] The ratio of the desalinated water output-volume to the seawater input-volume used to produce it is referred to as the recovery ratio.

1.3 Minimum number of membranes

The No BSR RO plant configuration employed for the modelling within this research is shown below in Figure 5.

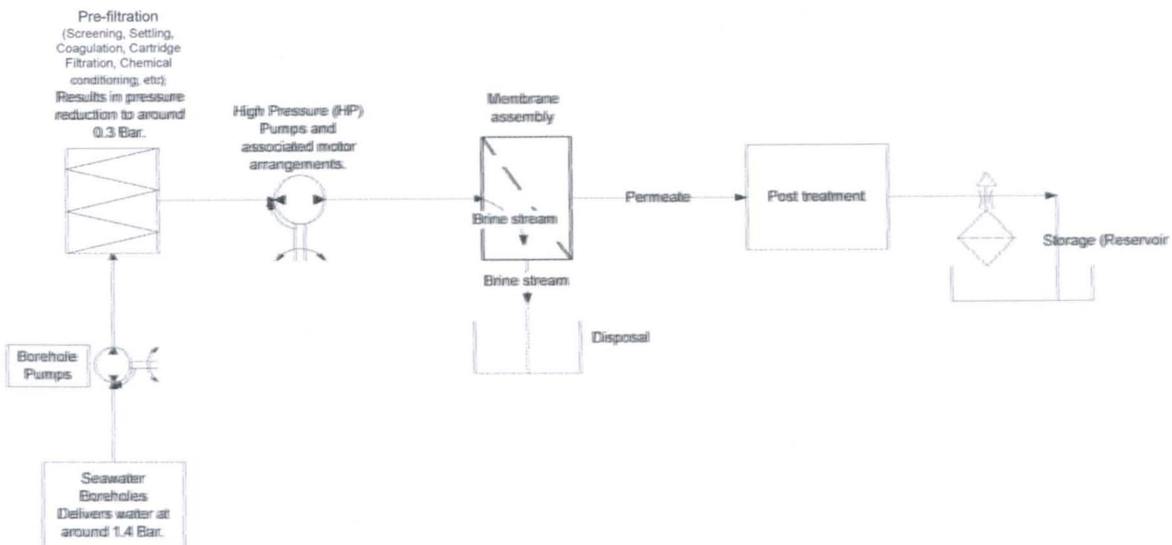

Figure 5: No BSR Plant type used within modelling.

The methodology used to identify the minimum number of elements and pressure vessels that would be required to meet the operational objective is shown below in Figure 6.

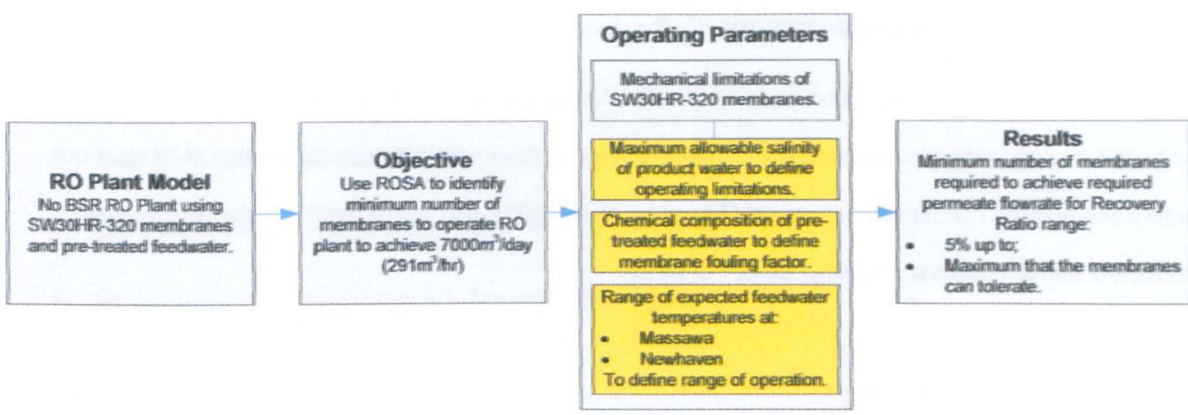

Figure 6: Methodology to identify minimum number of membranes that the no BSR RO plant requires.

To ensure that the cost of the RO plant was kept as low as possible, ROSA 6.2 [Dow] was used to identify the minimum number of membranes that would meet the operational objectives, which was to generate 7,000m^3/day (291.67m^3/hour). This was based on a simple plant without BSR (as shown above in Figure 5) operating continuously 24 hours per day, as it would if powered by conventional (non-intermittent) power supplies.

There were there main sets of parameters that required definition for ROSA 6.2 to identify the minimum number of membranes that would be required, and these are highlighted in yellow in Figure 6 above:

- The maximum allowable salinity of product water
- The chemical composition of the feedwater, and
- The expected feedwater temperature.

1.2.2 Water salinity

There was a need to ensure that the salinity concentration of the product water did not exceed the acceptable limit.

The allowable salt content was investigated based on the WHO guidance [WHO, 2011] on sodium and chloride. Chloride concentrations in excess of 250 mg/litre are likely to be detected by taste. No health-based guideline value is proposed for chloride in drinking water[4].

At room temperature, the average taste threshold for sodium is about 200 mg/litre. Again, no health-based guideline value has been derived[5].

As can be seen from the text above, there is no health-related threshold for salt in drinking water, and the only threshold advised is based on taste.

It was concluded that a threshold of 200 mg/litre of salt (chloride and sodium combined) would be employed as the salinity limitation for the output from the RO plants for this research.

1.2.3 Feedwater chemical composition

The seawater chemical composition used within ROSA was based on both the Newhaven and Massawa feedwater having undergone pre-treatment, as described in the chemical analysis section of 'Report on batteryless reverse osmosis desalination' [Thomson et al, 2001], and the modelling within ROSA was conducted with a 'membrane fouling factor'[6] of 85%.

---

[4] The 1958 WHO International Standards for Drinking-water suggested that concentrations of chloride greater than 600 mg/litre would markedly impair the potability of the water. The 1963 and 1971 International Standards retained this value as a maximum allowable or permissible concentration. In the first edition of the Guidelines for Drinking-water Quality, published in 1984, a guideline value of 250 mg/litre was established for chloride, based on taste considerations.
Source : WHO (2003) Chloride in drinking-water. Background document for preparation of WHO Guidelines for drinking-water quality. Geneva, World Health Organization (WHO/SDE/WSH/03.04/3).

[5] The 1958, 1963 and 1971 WHO International Standards for Drinking-water did not refer to sodium. In the first edition of the Guidelines for Drinking-water Quality, published in 1984, it was concluded that there was insufficient evidence to justify a guideline value for sodium in water based on health risk considerations, but it was noted that intake of sodium from drinking-water may be of greater significance in persons who require a sodium-restricted diet and bottle-fed infants.
Source: WHO (2003) Sodium in drinking-water. Background document for preparation of WHO Guidelines for drinking-water quality. Geneva, World Health Organization (WHO/SDE/WSH/03.04/15).

[6] 'Membrane fouling factor' is a projection of how a membrane may foul over time, and a factor 0.85 reflects a properly-designed systems with good pre-treatment. ROSA projects the membrane performance after 3 years of operation.

1.2.4 Seawater temperatures

As the RO plant feed water temperature increases, the permeate flow will increase for a given power level, but at the same time the salt passage will also increase.

The ambient seawater temperature varies at both sites, which will have an impact on the operating characteristics of the derived designs, in terms of power consumption and quality of permeate. The operation of the RO plants was modelled at the temperatures shown below in Table 1.

Table 1: Temperatures adopted for the Massawa and Newhaven

Level	Massawa[7]	Newhaven[8]
Maximum expected (most efficient)	37.8	16.5
Mid	25.3	10.8
Minimum expected (least efficient)	12.8	5.0

1.2.5 Reverse Osmosis Plant membrane limitations

These parameters were inputted to ROSA, and for defined levels of product water output (within the required salinity limits), the minimum number of membranes and minimum flowrate at which the membrane would produce water, were derived, within the limitations of the SW30HR-320membrane operating parameters, which were stored within ROSA.

The simplified typical RO membrane operating parameters are shown below in Figure 7, which indicates the limiting flowrates and pressure levels. If operated outside of these, the membrane will:

- Suffer mechanical damage due to excessive pressure/ brine flow rate (a and b)
- Not produce water due to inadequate brine flow (c), or
- Produce water with an unacceptable salt concentration (d).

---

[7] These figures were based on a visual assessment of the Red Sea water temperatures shown in Figure 14.

[8] These figures were based on range of expected seawater temperatures in the UK from http://www.chm.org.uk/library/ukprofilee.htm which states that:

'*Surface seawater temperatures range, in summer, from 12.5ºC around Orkney and Shetland to 16ºC in the English Channel, and, in winter, from 5ºC, off East Anglia and north-west England to 9ºC, in the extreme south-west of England.*'

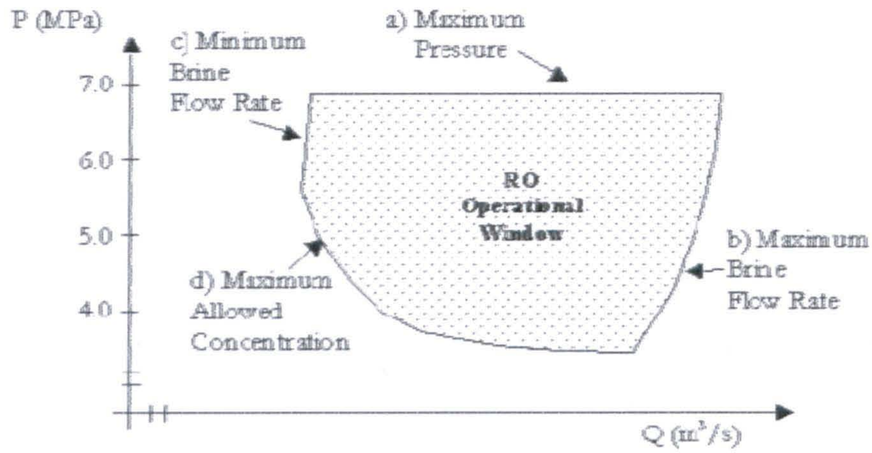

Figure 7: Typical Reverse Osmosis plant membrane operating window.

1.2.6 Identification of the minimum number of membranes required

An iterative process (Figure 8) was employed to identify the minimum number of membranes required.

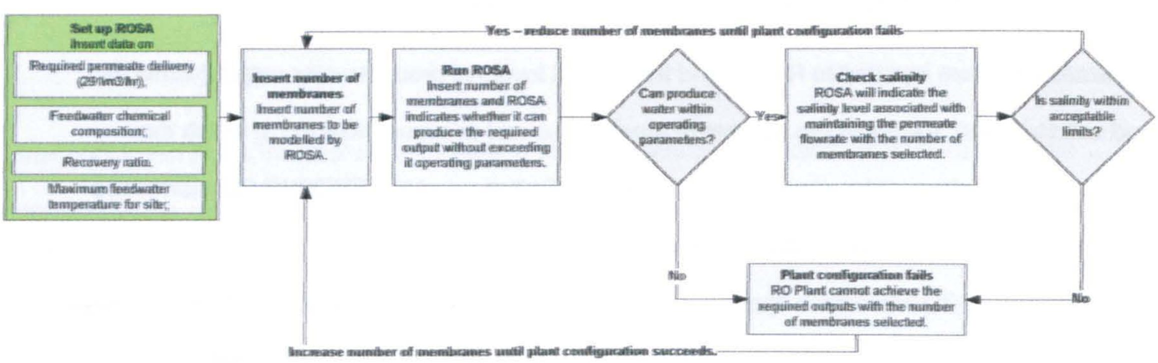

Figure 8: Identifying the minimum number of membranes.

This exercise was undertaken through the membrane's range of recovery ratios (from 5% to maximum limit, in 1% stages). The minimum number of membranes was identified for each recovery ratio by either:

- Reducing the numbers of membranes in steps until the plant configuration failed a mechanical limitation, and then noting the number of membranes set in the ROSA run immediately before the failure, or
- Increasing the number of membranes in steps until the plant configuration did not fail any of its mechanical limitations.

1.2.7 Results

The minimum number of membranes for each site was limited by the need to operate within their mechanical design limitations (see section on membrane limitations above).

The initial results from this exercise (shown below in Figure 9 below) gave the minimum number of membranes required to produce 7,000m^3/day, if the plant were run for 24 hours continuously at each recovery ratio.

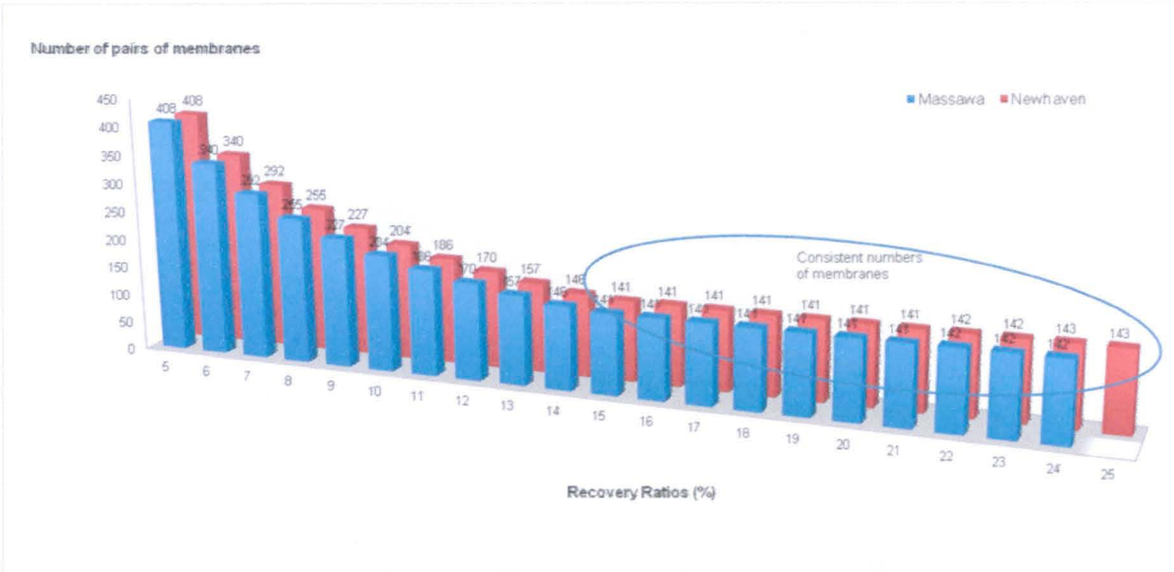

Figure 9: Minimum number of pairs of membranes at each site for maximum temperature at various recovery ratios

Figure 9 above shows that the minimum number of membranes required to produce the required amount of water, within the mechanical limitations of the membrane, varies with the recovery ratio. The ideal was to have a plant with a set number of membranes, which was also close to the optimum number of membranes. So it was decided that the RO plant would operate where the minimum number of membranes required was relatively consistent between 15% and 25% recovery ratios, as shown above in Figure 9.

1.2.8 RO plant design adopted.

The plant design adopted for this research was slightly simplified, and employed a set number of membranes (142 pairs), based on the output from ROSA. It operates between recovery ratios of:

- 15%, below which the minimum number of membranes required increased dramatically, and 24% and 25%, at Massawa and Newhaven, respectively, where the brine flowrate reduced to the minimum acceptable level.

The RO plant operating profile is shown below in Figure 10, in relation to the water output at varying recovery ratios. This design was used as the generic model for both the Newhaven and Massawa sites.

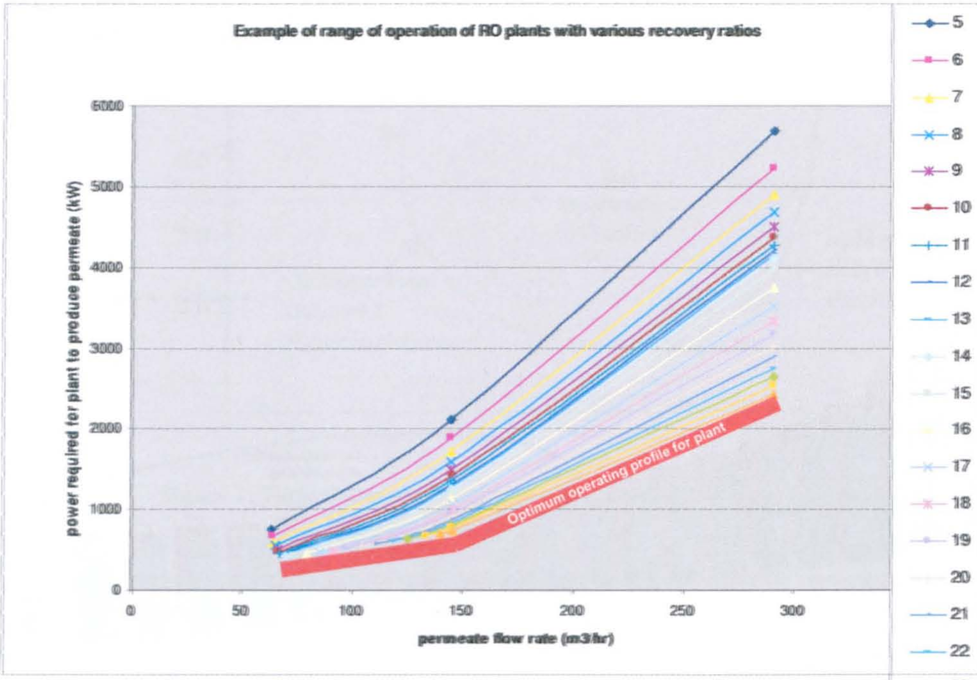

Figure 10: Optimum No BSR plant operating profile.

The optimum operating profile across the range of recovery ratios modelled (shown above in red, in Figure 10) is in keeping with the proposed optimum operating profile within the normal membrane operational window, shown below in Figure 11.

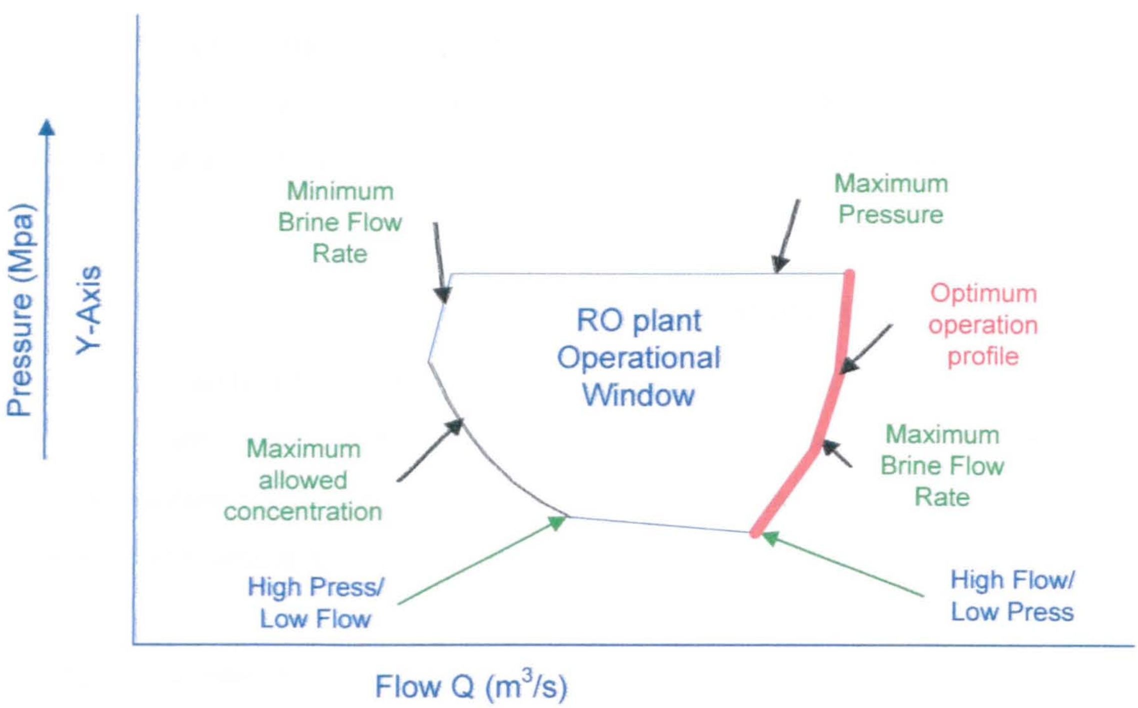

Figure 11: Optimum operating profile for RO plant from minimum to maximum flow

1.4 Movement of feedwater

In addition to pressurisation power requirements, there is a need to move feedwater from the intake, in preparation for pressurisation.

Table 2 below shows the values used to model the feedwater delivery process, for the No BSR plant.

Table 2: Power used by the No BSR RO plant to move feedwater

Type of pump and details*	Volume pumped		Power consumed (kW)	Power consumed per m^3 pumped (kW/m^3)
	(m^3/hr)	(m^3/sec)		
Seawater Borehole Pumps - Take water from static to around 0.3 bar[9] as suction for HP Pump.	110	0.03056	79.4	2599

* Details of feedwater movement power consumption taken from 'Design of a 10,000 cu-m/d Seawater Reverse Osmosis Plant on Providence Island' [Andrews et al].

To achieve these various flow rates of feedwater delivery and membrane pressurisation due to expected variations in available power, there is a need to vary flowrate. The working assumption was that that the pump and motor system act at 80% efficiency across their full working range.

This constant efficiency is probably unreasonable due to friction, windage losses, design for maximum efficiency at a specific load, etc. The only RO plant power being modelled is due to pumping, therefore the impact on the operating profile due to pump efficiency is likely to be significant. An example of expected pump efficiency was found in the US Department of Energy Tip sheet 2 [DOE, 2007], which allowed the relationship between pumping efficiency and the proportion of maximum load to be defined, which is shown below in Figure 12.

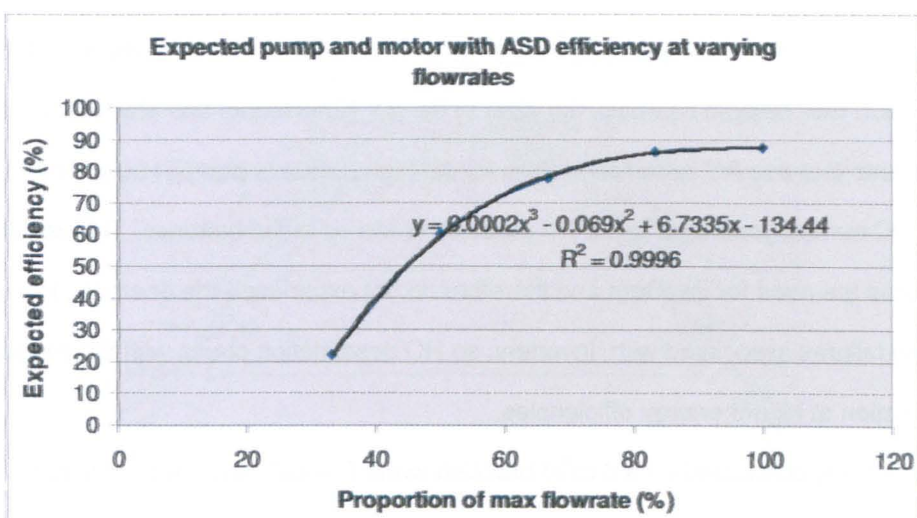

Figure 12: Expected efficiency of pump and motor at various proportions of flowrate

---

[9] Pre-filtration is assumed to reduce feedwater pressure from 1.4 bar to 0.3 bar at the inlet to the high pressure pump.

The polynomial equation that corresponds to the curve is included in Figure 12 above. These figures were applied to the range of temperatures for the No BSR RO plant. The resulting No BSR RO plant operating profile (including this refinement) is shown below in Figure 13.

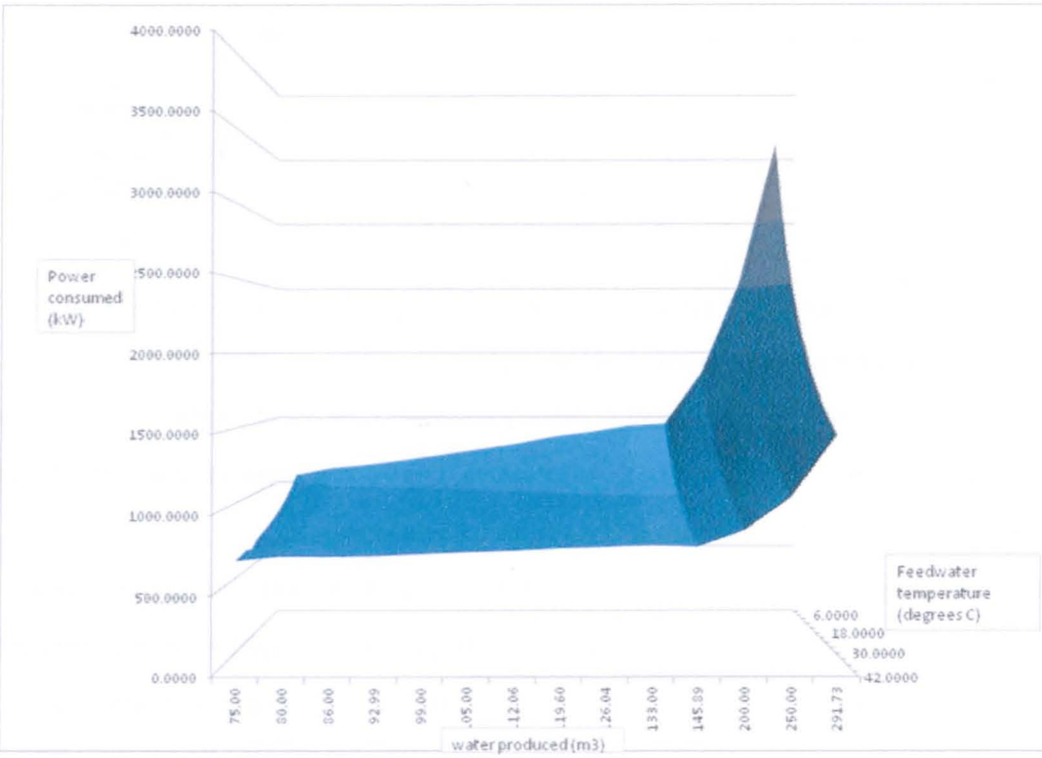

Figure 13: Operating profile of simple plant at strategic feedwater temperatures with varying pump efficiency

1.5 Use of AC power

In this case, it is assumed that AC power will be employed for the RO plant. As stated in 'Solar-driven desalination with reverse osmosis: the state of the art' [Ghermandi and Masselam, 2009] Desalination plants that use AC induction motors for the high pressure pumps require inverters to transform the DC current generated in the PV modules or stored in the batteries. The use of DC motors eliminates the need for inverters and therefore do not experience the energetic losses inherent in, and failures associated with, inverters, so RO desalination plants with DC motors are expected to function at higher energy efficiencies.

In spite of this, a study conducted on a 6 m^3/d brackish water PV–RO desalination system experienced steadier operation and significantly lower energy consumption (3 kWh/m^3 vs. 4.7 kWh/m^3) after replacing a DC motor with an AC induction motor [Marques de Carvalho et al, 2009]. This is borne out, according to De-central Water and Power Supply Integrating Renewable Energy – Technical and Economic Performance Prediction [Rheinlander, 2007], when a 0.25m^3/hr plant was run in two different configurations with:

1. A DC motor
2. An AC induction motor

It was found that the DC motor was not as suitable as the AC induction motor, which required less maintenance and reduced the specific energy consumption.

Considering the information available, it is concluded that although AC induction motors have been adopted for this research as the easier to operate and more efficient option, that DC motor configurations are available and have many technical benefits over AC, but do not appear to be achieving their potential in practice. It is considered that they are worthy of further investigation.

It is recommended that the potential benefits associated with the use of variable DC motors for reverse osmosis desalination is investigated further.

1.6 Defining feedwater temperatures for each site for each hour of the year.

To refine the model, the average feedwater temperature was calculated for each hour of the day for one year at each site.

For Massawa, the temperature profile for the Red Sea was taken directly from the thesis by A Murray Thomson [Thomson, 2003a]. The six years of data were superimposed, and a sine curve was fitted, as shown in Figure 14 below.

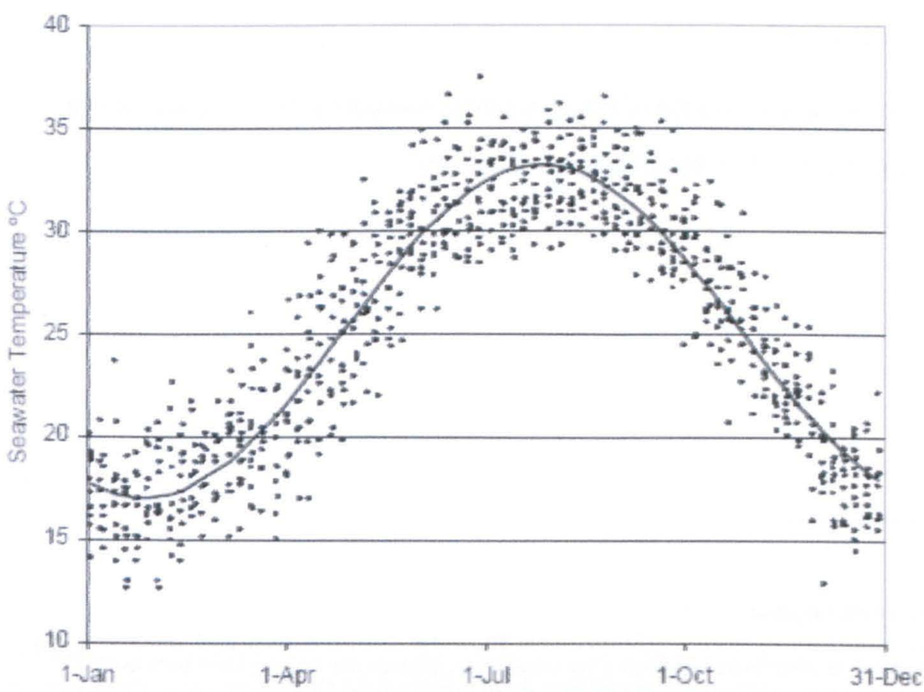

Figure 14: Red Sea water temperature with fitted sine curve.

The equation associated with the curve shown in Figure 14 above is:

Massawa seawater temperature = 25+ 8 sin (2 π (day of year-118)/ 365))

The data for Newhaven was taken from Eastbourne [CEFAS, 2011], which is 10 miles (16km) away from Newhaven, and the data was approximated to a polynomial curve, shown below in Figure15.

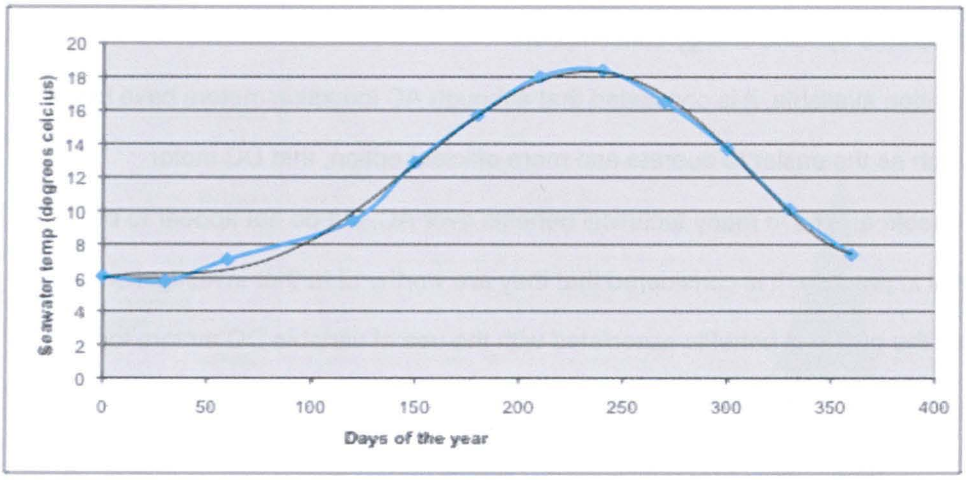

Figure 15: Seawater temperature curve for Eastbourne

The relationship between seawater temperature (*T*) and day (*x*) of the year is given by:

$$T = 0.000000000034 * x^5 - 0.000000015 * x^4 - 0.0000024x^3 + 0.0014 * x^2 - 0.06 * x + 6.2$$

For the purposes of this research, the plant at both sites provides water for domestic and light industrial (including offices) use. At both locations it was modeled as running continuously for 12 months of the year, to meet all the domestic and light industrial needs of the town[10].

1.7 Amount of water required

To allow a measure of the effectiveness of the RO plant, a simple relationship of the impacts due to reduced flowrates was developed, and is shown below in Figure 16.

[10] **Duty of the plant in South East England.**

In reality, the envisaged operation of desalination in the South East of England is purely to manage peak demands during years when there is high demand, or when there has been a dry winter when groundwater has not been sufficiently recharged. As such, it is expected that an RO plant at this location would run for around 8 months at a time, once every 5 to 10 years.

It would be used to supplement existing established water supplies, and will run continuously for eight months of the year, nominally March to November inclusive.

(Taken from e-mail from James Grinnell, then Water Resources Manager, South East Water. 17 October 2005).

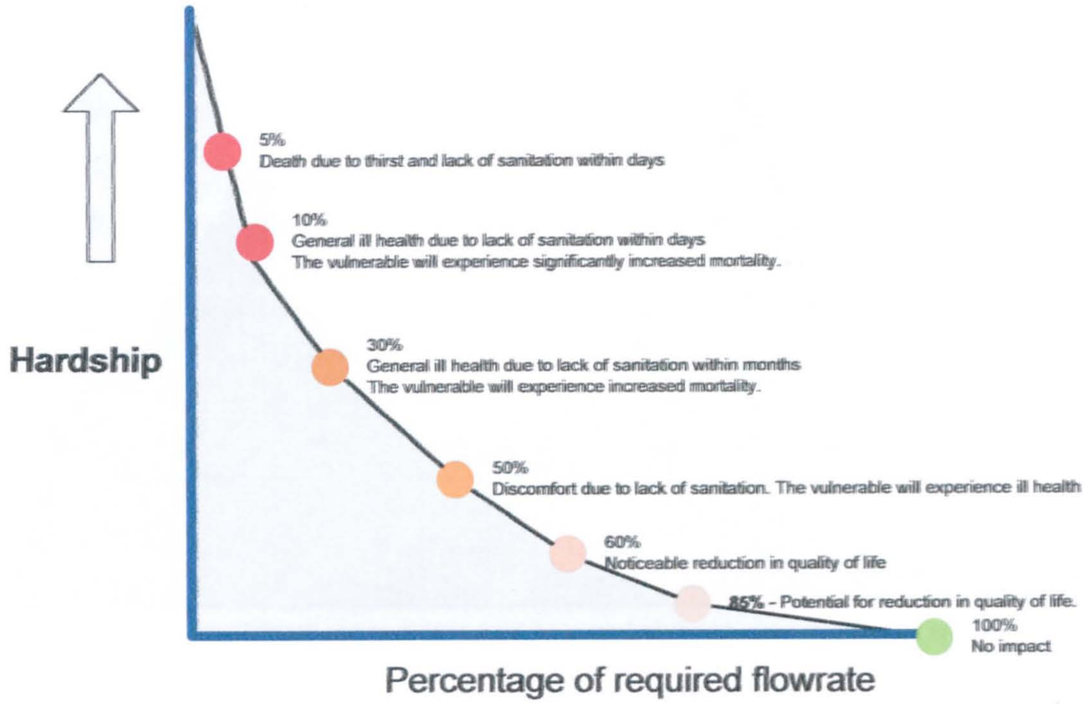

Figure 16: Impact on human health of varying degrees of water shortage

Figure 16 above indicates the impact on human health, expected hardship, and required external intervention points at reduced levels of water production from the RO plant, in terms of the proportion of maximum design water delivery. Based on this model, no action would be taken until water production fell below 85% of the full flowrate. The identification and reaction to flowrates below 85% would need to be developed along the lines of the drought plan methodology explained at the Environment Agency website[11].

The profiles for water use were based on the usage chart in Figure 17 below. This shows the rolling hourly water consumption[12] for an individual property in the UK, and distinguishes between water used inside and outside of the house on a summer peak water use weekday [Defra, 2008].

[11] The identification and reaction to flowrates below 85% would need to be developed using the drought plan methodology, as explained by the Environment Agency website at http://www.environment-agency.gov.uk/homeandleisure/drought/31771.aspx [Last viewed on 7 August 2011].

[12] The unit of volume consumed is based on rolling hours, i.e. if the rate of water consumption in any given 15-minute period was sustained for 24 hours, the total volume consumed would be as per the height of the bar.

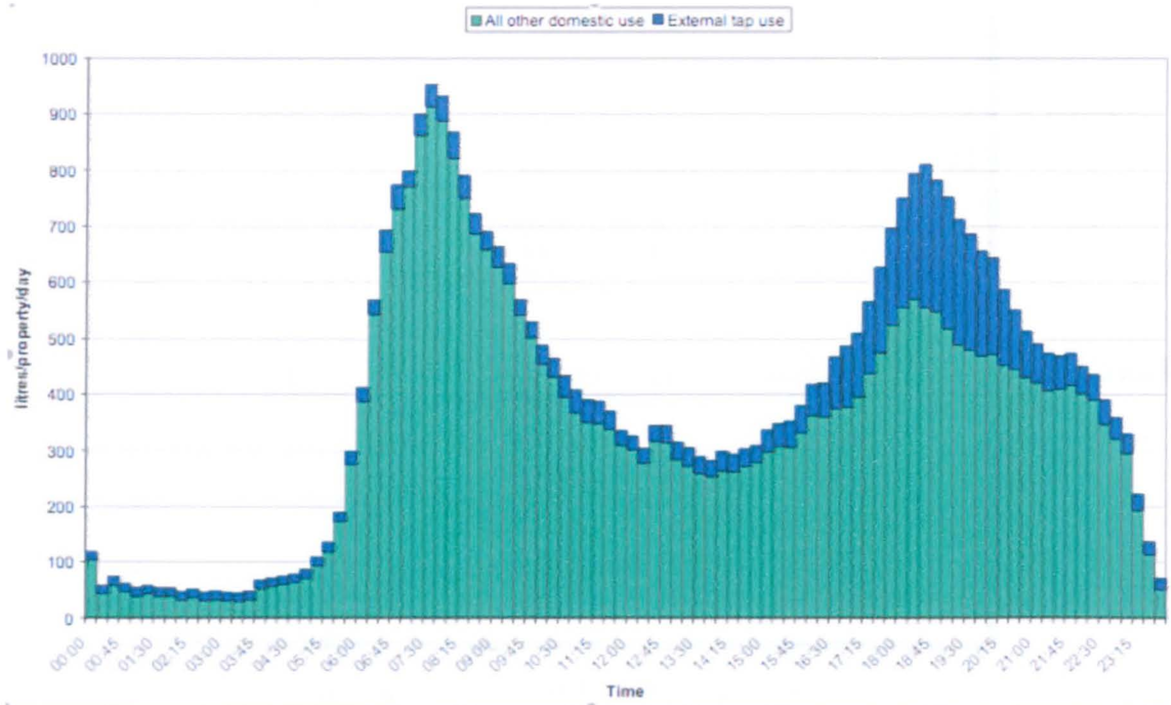

Figure 17: Water consumption for an area of Eastbourne over 2 days.

The daily water use profile shown above was used as the basis for the daily water use profile employed within this thesis[13]. The daily water use was proportioned for the total water requirement from the RO plant, and for simplicity, no seasonal variations were included. This much-simplified daily water usage cycle is shown below in Figure 18.

[13] The water uasage profile can be explained as follows:

- Low water use from midnight until 05:30 when people start to get up in the morning, make tea or coffee, run a bath, or have a shower.
- Water use activity carries on through the day with washing machines being used, dishes being washed, lunches being prepared but most water is used in the morning.
- In the afternoon, there is a slight reduction in water consumption as people go out, but from 16:00 onwards consumption increases as supper is prepared, gardens are watered, and children are bathed. It then reduces in the late evening as people go to bed.

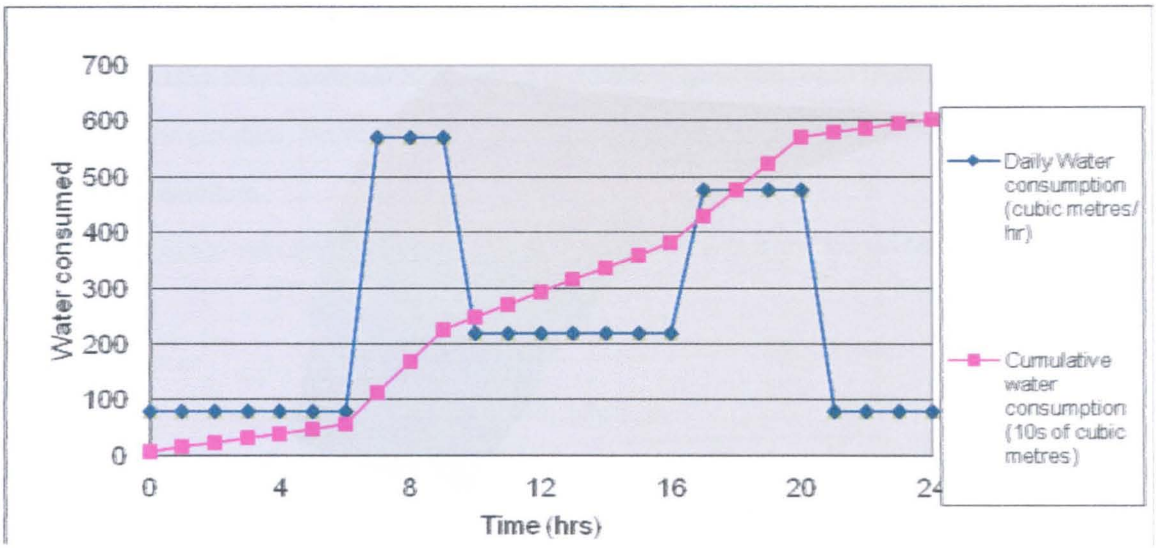

Figure 18: Daily water usage cycle

This profile consumes 5950m^3 of water over a 24-hour period, which equates to 85% of the 7000m^3 required daily water production for 50,000 people.This is the minimum water consumption before intervention to manage the lack of water is implemented, and will result in the greatest reservoir size that can reasonably be expected (and should be designed for).

1.8 Modelling water production from No BSR RO plant

A 3-dimensional surface of the No BSR RO plant profile was developed in Matlab[14], as shown below in Figure 19. This correlates the:

- Feedwater temperature
- The water produced, and
- The energy consumed for the corresponding water produced, at the specific feedwater temperature.

[14] Matlab is a high-level language and interactive environment that allowed the vast amounts of data required to model the RO plant operating profiles, to be manipulated more easily than Microsoft Office Excel spreadsheets. Greater detail of the Matlab software is available at http://www.mathworks.co.uk/ [Last viewed on 7 August 2011].

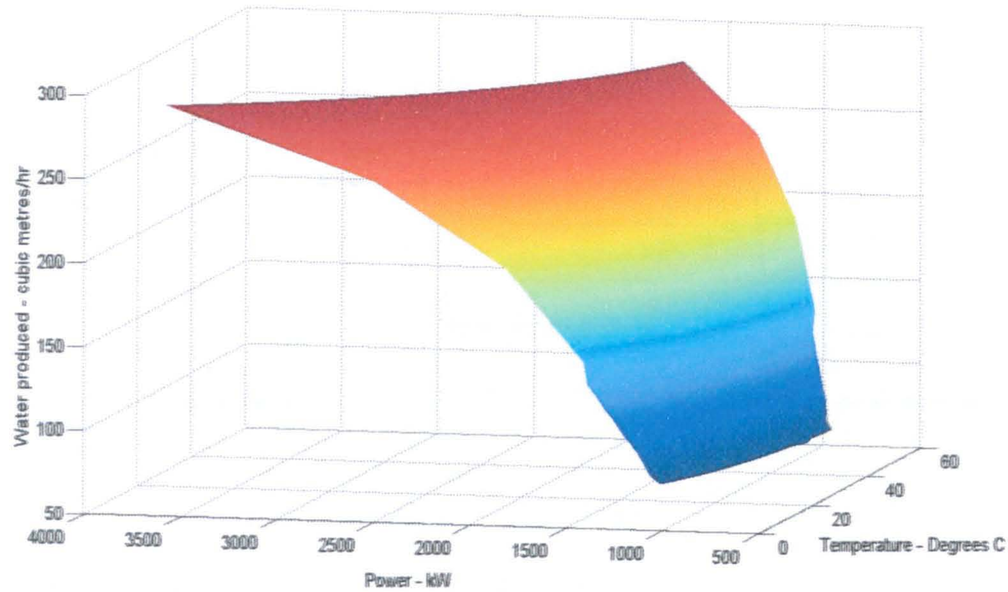

Figure 19: No BSR RO Plant water production profile at varying power and feedwater temperature

The above profile was then manipulated using polynomial approximations (as explained in the following section), so that it could be interrogated for any combination of feedwater temperature and power available, to calculate the amount of water delivered[15].

The methodology employed to calculate the amount of water produced involved taking the data for 'power available' vs. feedwater temperature for each individual water delivery setting from minimum ($75m^3/hr$) to maximum ($291m^3/hr$), and deriving the corresponding polynomial equations for each of the 14 discrete water delivery curves, as shown as red lines connecting the blue sampling points below in Figure 20.

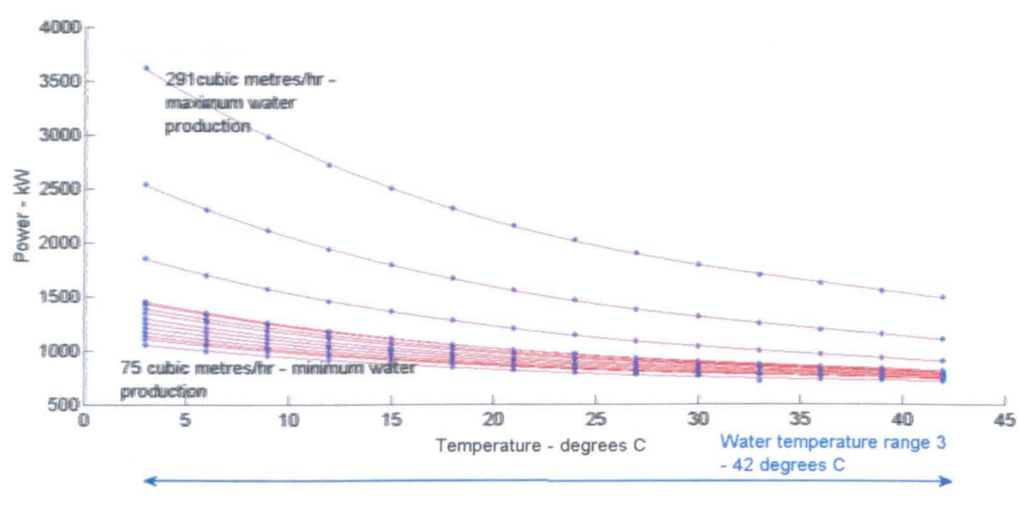

Figure 20: Approximating curves for various levels of water production from the No BSR RO plant

[15] A significant amount of time was spent previously in pursuit of the single unifying equation that would allow any input value of power and feedwater temperature to calculate the corresponding water delivery for the surface. This was eventually abandoned, and it was decided to pursue a less accurate method but which was easier to implement.

From this set of polynomials, the feedwater temperatures were split further from 3ºC intervals to 0.01ºC intervals. This ultimately resulted in 3901 sets of quadratic polynomials, each relating to a 0.01 ºC step in feedwater temperature, representing the amount of water produced from the power delivered, at that feedwater temperature.

The method used to calculate the amount of water generated, was a 'for' loop in Matlab, as shown below:

```
for i=1:rwr
    newwater1(i) =polyval(ppolycoef(index(i),:),Pg1(i,:));
end
```

where:

Pg 1 = the power available to operate the RO plant at each hour during the year.

index(i) identifies the location of the prevailing seawater temperature for each hour of the year.

ppolycoeff is a file that contains all the polynomial equations relating to each 0.01°C step from 3 – 42 °C.

i=1:rwr defines the number of times that the calculation should be conducted before stopping.

i=the number of the calculation being conducted, in this case, conducted in sequence from 1 – (rwr) the max number which is 8760 (the number of hours in a year).

Polyval is the matlab function that then evaluates the polynomial equation identified by *(index(i))* making the corresponding *Pg* at *(i)* the subject.

1.9 Model of non-varying power source

The power demand for the No BSR RO plant (as would be supplied by a non-varying power source) is shown below in Figure 21.

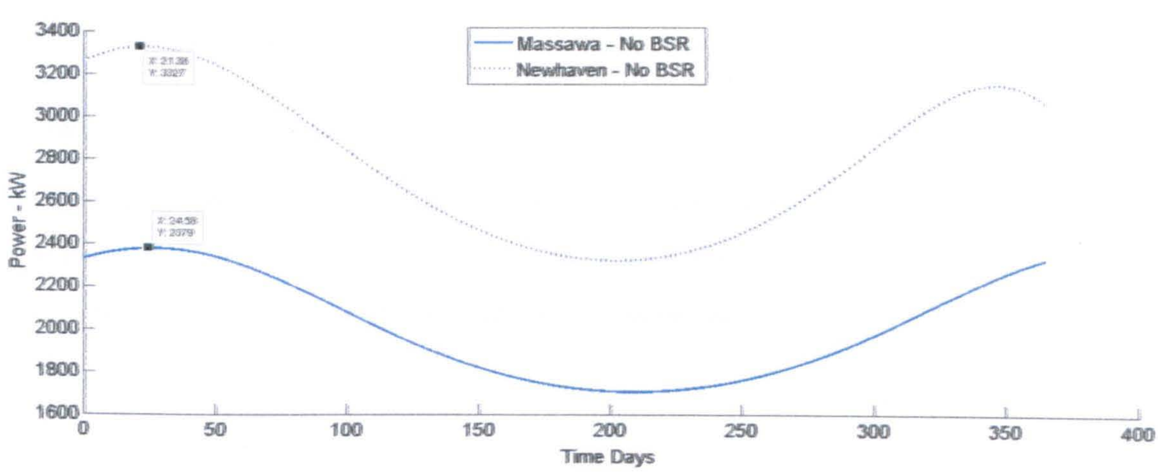

Figure 21: No BSR power profile over 1 year to maintain maximum flowrate at Massawa and Newhaven

As shown in Figure 21 above, Newhaven requires its maximum input of 3327.74kW at 23 days and 1 hr. For the purposes of this research, the plant size that the renewable energy system was compared to, was a conventional plant of 3,400kW.

Also shown at Figure 21 above, Massawa requires its maximum input of 2379kW at 24 days and 12 hrs. For the purposes of this research, the plant size that the renewable energy system was compared to, was a conventionally plant delivering 2,400kW.

2 Most reliable Renewable Energy Sources

It was decided that each site should employ the most reliable renewable energy resource available to them. This resulted in the application of renewable energy as follows:

- Massawa – Solar Energy
- Newhaven – Tidal Current Energy

The scenario illustrated in Figure 22 was modelled for both sites to represent the single source renewable energy.

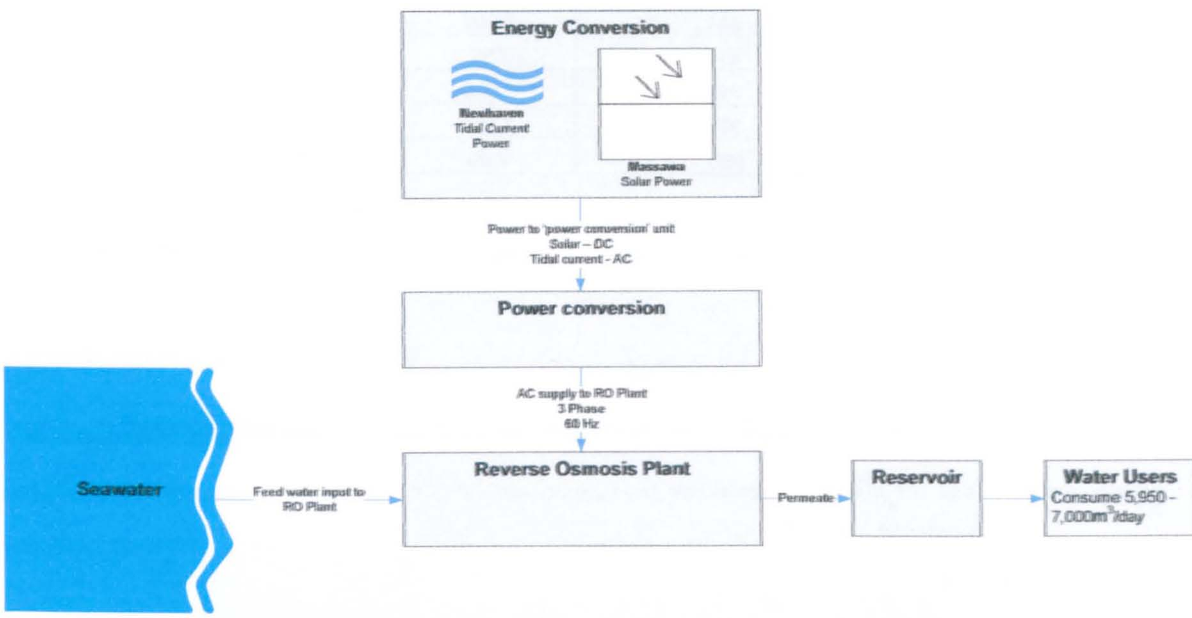

Figure 22: Single source of renewable energy to power RO plant at both sites.

2.1 Massawa - Solar Power

Massawa is reportedly one of the hottest inhabited places in the world[16], with the temperature reaching 46°C in May. Also, due to geographical reasons that preclude the use of tidal current power[17], solar power was adopted as the most reliable renewable energy source.

---

[16] Farlex encyclopaedia available at http://encyclopedia.farlex.com/Massawa [Last viewed on 7 August 2011].

[17] The Red Sea is an enormous basin locked in the north by the Suez Canal and in the south by the Strait of Bab al Mandeb, just 300 feet deep, thereby clearly cut off from the currents of the Indian Ocean and Mediterranean Sea, resulting in the elimination of a tidal system. Therefore, tidal current power is not available.

HOMER (energy modelling software for renewable energy systems)[18] was employed to derive the solar irradiance on an hour-by-hour basis at Massawa, based on the monthly averages [Thomson, 2003b], as shown below in Table 3.

Table 3: Average monthly irradiance

Month	Original monthly average (W/m^2/day during that day)	Conversion to kW/hr	Clearness index[19] applied by HOMER
Jan	303	7.272	0.895
Feb	357	8.568	0.954
Mar	366	8.784	0.884
Apr	376	9.024	0.855
May	337	8.088	0.754
Jun	306	7.344	0.686
Jul	300	7.2	0.674
Aug	301	7.224	0.684
Sep	330	7.92	0.784
Oct	319	7.656	0.830
Nov	308	7.392	0.891
Dec	295	7.08	0.905

The original data was converted into a format suitable for HOMER, which when inputted to HOMER generated the:

- Appropriate 'clearness index' to be applied, and
- An hour-by-hour irradiance profile in terms of W/m^2, which is shown below in Figure 23[20].

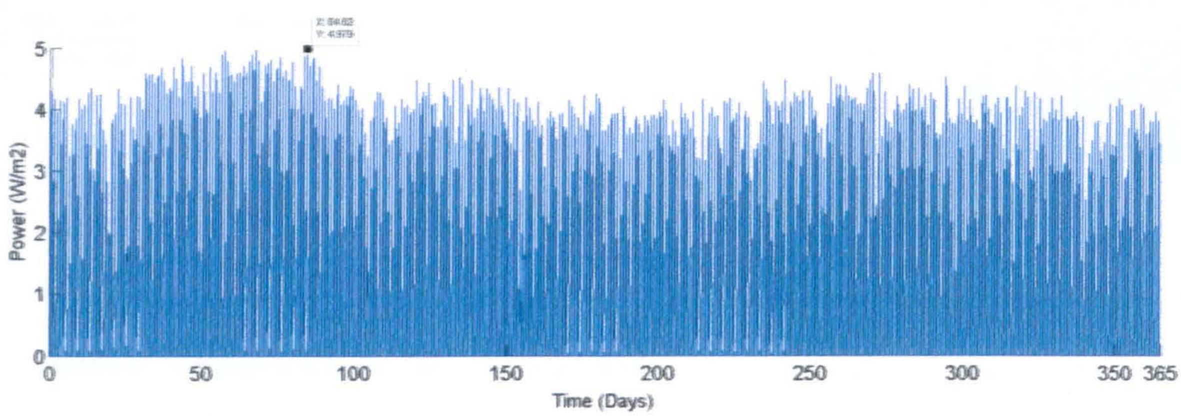

Figure 23: Hourly irradiance at Massawa over one year

As can be seen from Figure 23 above, the maximum irradiance during the year was 4.979 W/m^2.

---

[18] The HOMER energy modelling software is used for designing and analysing hybrid power systems, and is available at http://homerenergy.com/ [Last viewed on 7 August 2011].

[19] The 'clearness index' is a dimensionless number between 0 and 1 indicating the fraction of the solar radiation at the top of the atmosphere that is able to pass through the atmosphere to the Earth's surface. Greater detail of its derivation within HOMER is available within the 'Help' pages of HOMER.

[20] This was based on the setting for East Africa (GMT +3hr) at 15º 36' 33"N. 39º 26' 43"E

2.1.1 Semi-Conductor Solar Cell Operation

The operation of a semi-conductor solar cell is illustrated by the example of a p-n junction, shown below, in Figure 24. This depicts the electric field, which tends to drive free electrons to the n-type material and into the electrical circuit.

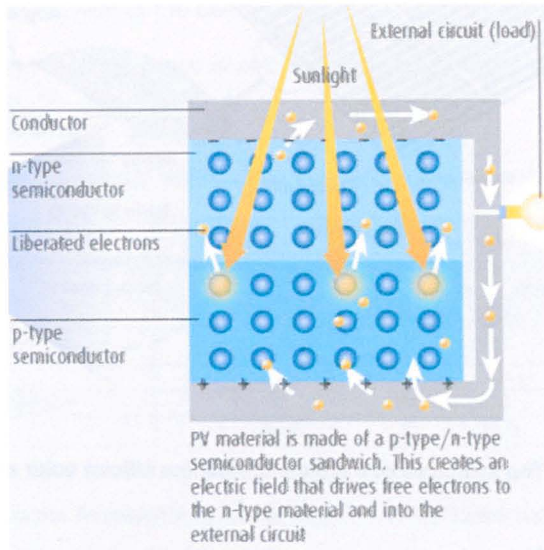

Figure 24: PV solar cell conversion process

2.1.2 Typical silicon solar cell

The structure of a typical silicon solar cell is illustrated in Figure 25 below. The electrical current generated in the semi-conductor is extracted by contacts to the front and rear of the cell. The top contact structure, (which must allow light to pass through), is made in the form of widely-spaced thin metal strips (usually called fingers), that supply current to a larger bus bar. The cell is covered with a thin layer of dielectric material that acts as an anti-reflection coating (ARC) to minimise light reflection from the top surface.

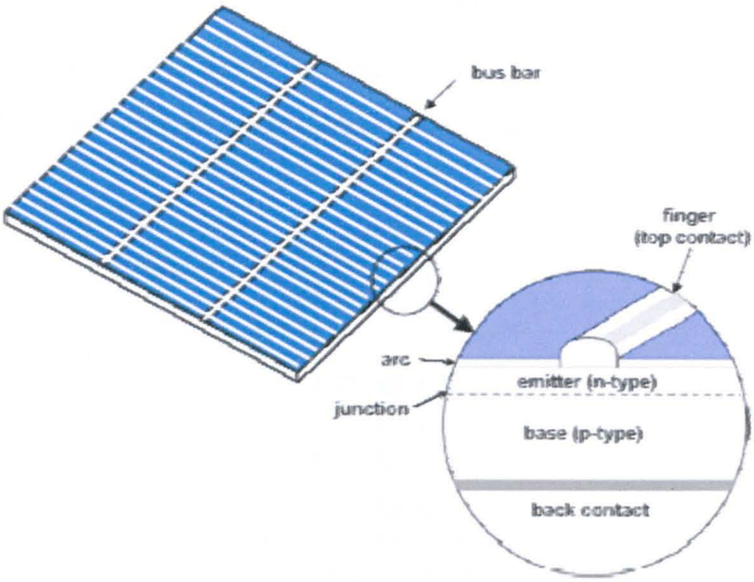

Figure 25: The structure of a typical crystalline silicon solar cell.

2.1.3 Losses in a solar cell

Reflective and other losses (e.g. shading and incomplete absorption of light) reduce the typical efficiency of commercial devices to roughly 50% of the achievable maximum[21].

2.1.4 Measures taken to reduce these losses

Measures taken to reduce these losses include the use of:

- Multi-layer anti-reflection coatings
- Surface texturing to form small pyramids, and

---

[21] A loss mechanism present in all practical devices is non-radiative recombination of the photo generated electron-hole pairs. Such recombination is most common at impurities and defects of the crystal structure, or at the surface of the semi-conductor where energy levels may be introduced inside the energy gap. These levels act as stepping stones for the electrons to fall back into the valence band and recombine with holes.
The losses due to bandgap energy can be reduced, but only by utilising more complex structures based on:

- Several semiconductors with different bandgaps, and/ or;
- Concentrating the solar irradiance.

Collection efficiency
The losses to current by recombination are usually grouped under the term of collection efficiency, which is the ratio between the number of carriers generated by light and the number that reaches the junction. In crystalline materials, the transport properties are usually good, and carrier transport by simple diffusion is sufficiently effective. In amorphous and polycrystalline thin films, however, electric fields are needed to pull the carriers. The junction region is then made wider to absorb the main part of the photon flux.
Other losses to the current produced by the cell arise from:

- Light reflection from the top surface;
- Shading of the cell by the top contacts, and;
- Incomplete absorption of light.

The last feature can be particularly significant for crystalline silicon cells since silicon (being an indirect-gap semiconductor) has poor light absorption properties.
Another common loss in commercial cells involves ohmic losses in the transmission of electric current produced by the solar cell, usually grouped together as a series resistance, which reduce the fill factor of the cell.

- Making the back contact optically reflecting, which when combined with a textured top surface, results in effective light trapping, which provides a good countermeasure for the low absorptivity of silicon.

Top-contact shading is reduced in some cells by forming these contacts in narrow laser grooves, or all the contacts can be moved to the rear of the cell.

The principal characteristics of different types of cell in or near commercial production, are summarised in Table 4 below.

Table 4 : Solar cell efficiencies achieved by the principal semiconductor technologies

Material	Efficiency (%)		Technology employed
	Commercially available	Best R&D [Green et al, 2008]	
Mono- or multi-crystalline silicon	10 - 18	25	Ingot/ wafer
Amorphous silicon	5 - 8	10	Thin film
Copper indium gallium Selenide*	8	16	Thin film
Cadmium telluride**	10.6	16.5	Thin film

* Also see article from Swiss Metal Assets [Swiss Metal Assets, 2010], which indicates some of the advances being made with this technology. This article indicates that the thin film copper indium gallium selenide (CIGS) technology which is particularly flexible in use, is rapidly advancing on the efficiency of the more expensive crystalline silicon photo voltaic cells.

** *Taken from 'Cadmium Telluride – The Good and the Bad' [Solar Facts and Advice, 2010].*

2.1.5 Device employed within model

The device employed within the research was mono-crystalline silicon, modelled as being 10% efficient. This was the worst case for its efficiency, shown above in Table 4.

The solar array for this process assumes that 10% of the available radiation, at any time when the sun is shining, is captured and converted to usable electrical power.

2.1.6 Conversion of Solar DC Power

It was modelled that the PV cells would supply DC power. This DC supply would be converted by an inverter to AC, suitable for use by the RO plant. The efficiency of this power conversion was taken as between 90 and 95%.

2.2 Newhaven – Tidal Power

The maximum tidal current speed on the south east coast of England (about 1.75 metres per second) is at Dover, owing to the restriction of the English Channel around that area. The tidal speed around

Newhaven is quoted [MTMC, 2007] as being up to 1.5 m/sec[22], and for the purposes of this research, it was assumed to be 1.49 m/s.

One year's data (for 2004) for Newhaven was taken from the National Tidal & Sea Level facility (National Oceanographic Centre, 2011] in the form of tidal range information, which was converted to water speed[23]. The resulting tidal speed profile for each hour over the course of one year, is shown on the graph below in Figure 26.

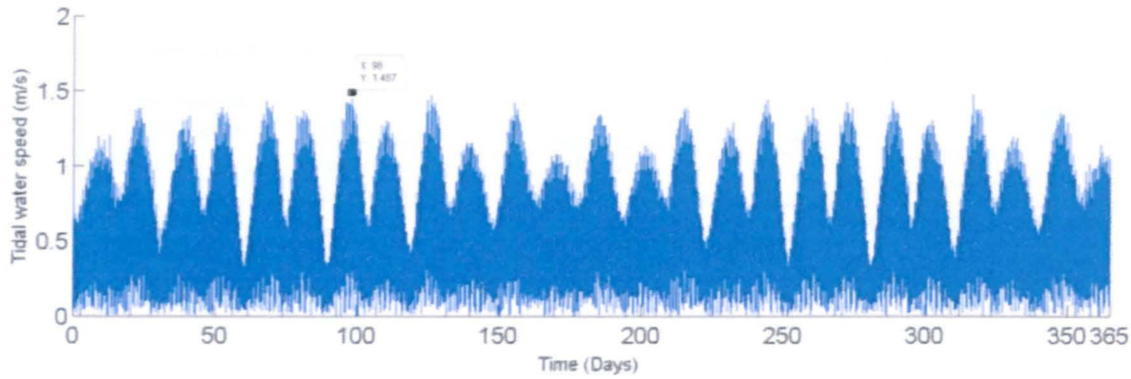

Figure 26: Tidal speeds in Newhaven for 2004 (in m/s) at hourly intervals.

As can be seen from above, the maximum tide speed during the year at Newhaven was 1.487m/s.

2.2.1 Tidal Current Devices

There are a variety of devices available to collect and convert tidal power to electricity, which are explained in great detail at 'The Analysis of Tidal Stream Power' [Hardisity, 2009]. It was decided that the device that would be modelled would be as technically proven as possible and available to be installed now, but unlike solar and wind there is no standardised design and the available tidal current devices are at varying stages of development, and few are at the commercial implementation stage.

So, from the multitude of tidal device options available, the SeaGen Turbine device was selected for use in this research[24], and is shown below in Figure 27.

---

[22] The spring tide mean peak flow is quoted as 1.25 – 1.5m/s off shore between Portsmouth and Eastbourne. It is noteworthy that this is some distance offshore. Locating the devices closer to shore results in a significant reduction in tidal current speed.

[23] The tide height was converted to water speed by:

- Calculating the tide heights at each hour during the year, to give the rate of change of tide height for each hour
- Dimensioning the rate of change of tide heights, to fit the 1.5m/s max flowrate adopted at mid-spring tide, and 0m/s at high and low tide
- Assigning speed in proportion to the rate of change of height for the rest of the year
- Root mean square average taken for the data over the course of the year, to provide an average daily cycle to regularise, so that all the values were positive, based on the assumption that power can be generated as the tide flows in both directions.

[24] See 'Sea Generation Limited' Webpage at http://www.Seageneration.co.uk/ for further details. [Last viewed on 7 August 2011]. By using twin rotors, Marine Current Turbines estimate that they can achieve double the power for only 60% extra

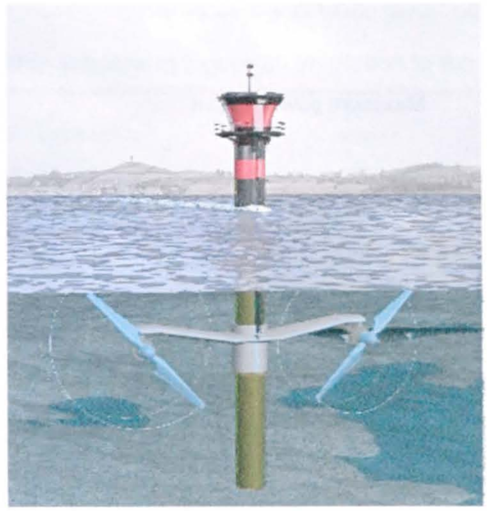

Figure 27: Marine Current Turbines Limited SeaGen Turbine

The reason for selecting the SeaGen was its relatively advanced status of development as shown at 'Marine and Hydrokinetic Technology Listings', a comprehensive database of current projects and their status compiled by the US Department of Energy [USDoE, 2012]. At the time of drafting it was the most advanced tidal current device, although quite closely followed by the Atlantis AR-1000, which is currently at the demonstration stage. Both the SeaGen and the Atlantis AR-1000[25] are MW scale horizontal axis devices.

2.2.2 Model of SeaGen Operation

The SeaGen Turbine's power output in relation to the prevailing tidal current speed was approximated using a fifth order polynomial, shown on the graph in Figure 28 below.

---

cost over a single turbine. Blades would only travel at a maximum of 12-15 m/s, which is taken to be slow enough so as not pose a danger to marine life.
A working example of a 1.2 MW Seagen tidal energy system was installed by Marine Current Turbines Ltd (MCT) in Strangford Lough in April 2008.

[25] Greater detail of the Atlantis AR-1000 and the and its manufacturer, Atlantis Resources Organisation, is available at their website http://www.atlantisresourcescorporation.com/ [Last viewed 1 September 2012].

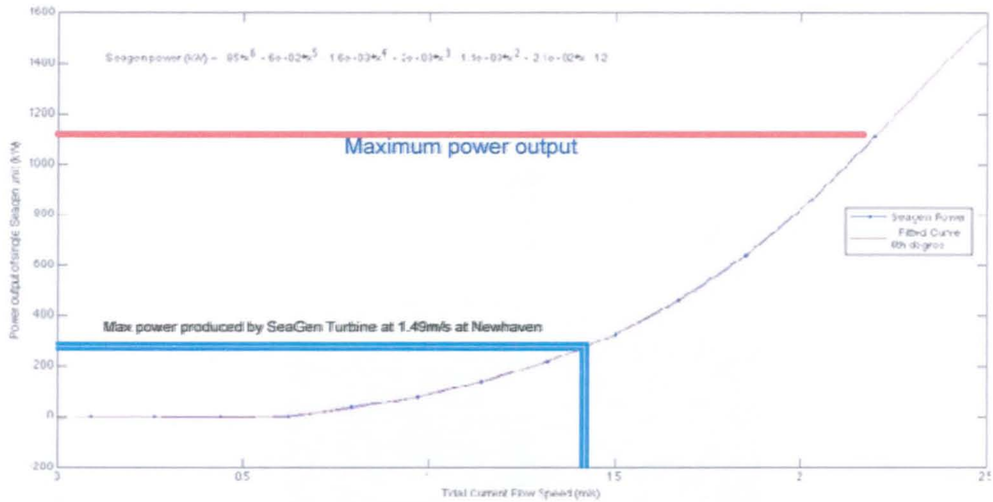

Figure 28: Power output of single SeaGen Turbine

It is noteworthy that due to the limited tidal current speeds at Newhaven, the SeaGen Turbine is (at best) not expected to achieve more than 1/3rd of its rated capacity during the year. This polynomial was applied to the tidal current speeds derived for Newhaven, resulting in the following power output (Figure 29) from a 1,113kW device.

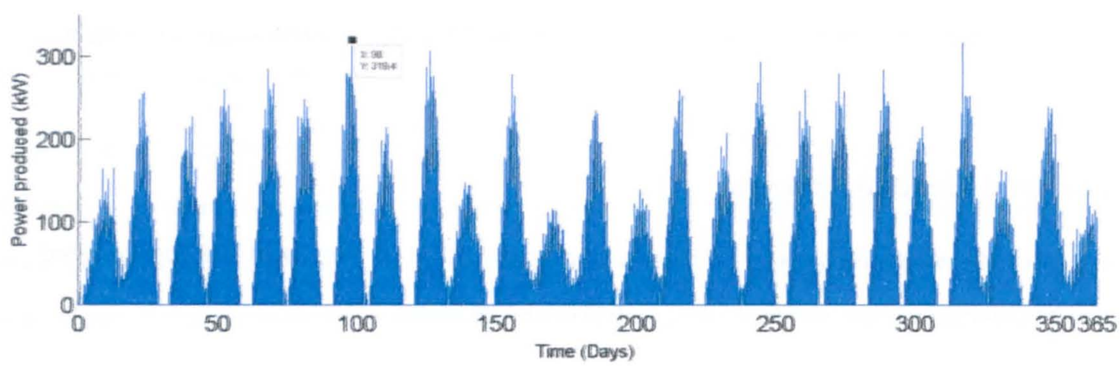

Figure 29: Power output (kW) from single SeaGen Turbine at Newhaven over 1 year (kW)

It is apparent that, although the main thrust of tidal current technology development is around the MW scale horizontal axis devices, they do not present a realistic option for the relatively low tidal speed environment at Newhaven. This said the SeaGen was modelled, as the most developed device, as an academic exercise, although it is appreciated that a more technically viable option would need to produce power at lower tidal current speeds.

2.2.3 Conversion of Tidal Current Power

The Tidal Current Turbine(s) was modelled to supply Alternating Current (AC) power. This AC would be converted to an AC waveform suitable for use by the RO plant using a transformer. The efficiency of this power conversion was taken as between 90 and 95%.

3 BSR Plants

The data definition stages are shown below in Figure 30 in relation to the modelling for the BSR RO plants.

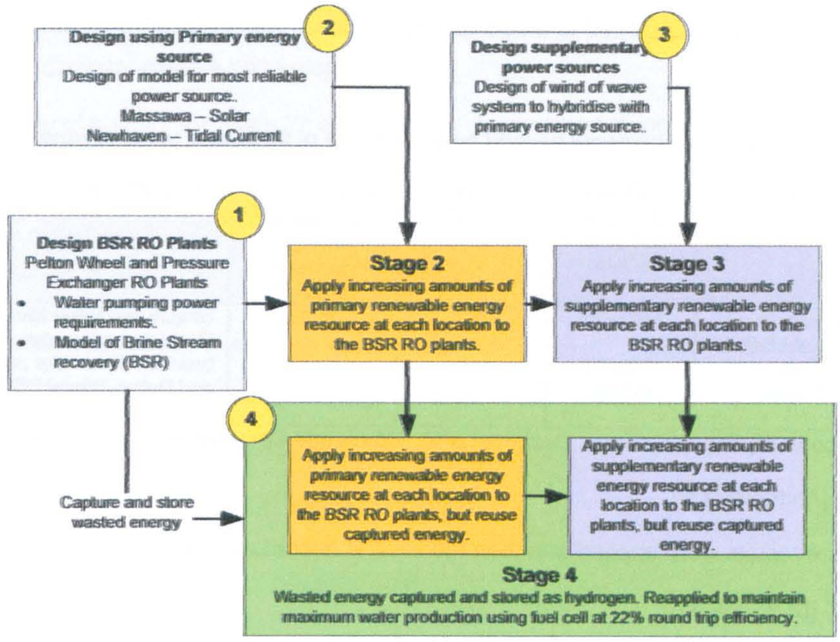

Figure 30: BSR RO Plant modelling process

The No BSR RO plant was modified to represent the operating profiles of the same capacity RO plant, but using the following BSR techniques:

- Pelton Wheel, and
- Pressure Exchanger.

3.1 Power demand

The power consumed by each of the BSR plants was modelled as:

- Power to pressurise feed, and
- Power to move feed/ process water as required.

3.1.1 Power to pressurise feed

All data for pressurisation power was derived from ROSA 6.2, and pressurisation power from ROSA was also applied to the booster pump on the Pressure Exchanger BSR reverse osmosis plant.

3.1.2 Movement of feed/ process water

In addition to pressurisation power requirements, for the Pelton Wheel BSR plants there is a need to move water away from site, having had all its energy extracted, and reapplied to the RO plant by the Pelton Wheel.

Table 5 below illustrates the values used to model all other process water power requirements for the BSR RO plants.

Table 5: Power requirements beyond pressurisation of feedwater at membranes

Type of pump and details*	Volume pumped m^3/hr - m^3/sec	Power consumed (kW)	Power consumed: For each m^3 of water pumped (kW/m^3)	Applicability
Seawater Borehole Pump - takes water from static to around 0.3 bar[26] as suction for HP Pump.	110 m^3/hr 0.03056 m^3/sec	79.4	2599	Simple and Brine Stream Recovery options as borehole feedwater pump, and Pelton Wheel BSR plant brine removal.

* Details of power consumption taken from 'Design of a 10,000 cu-m/d Seawater Reverse Osmosis Plant on Providence Island' [Andrews et al]

As previously, these results were applied and then modified in accordance with 'Pumping efficiency at Varying Flowrates' [DOE, 2007].

3.2 Pelton Wheel

The Pelton Wheel RO plant system modelled is shown below in Figure 31.

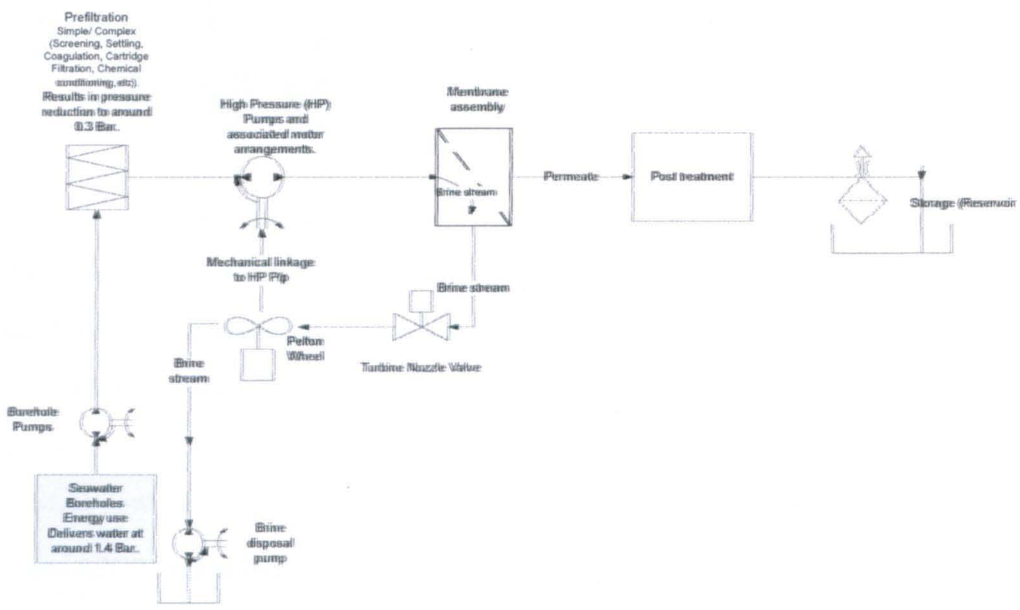

Figure 31: Simple plant using Pelton Wheel for BSR design

---

[26] Prefiltration assumed to reduce pressure from 1.4 bar to 0.3 bar at the inlet to the membrane pressure vessel.

As shown in Figure 31 above, the Pelton Wheel BSR RO plant design utilises the brine stream to power a Pelton Wheel turbine, which is mechanically linked to a high pressure pump (HP p/p) arrangement. The power produced from the Pelton Wheel is used to partially pressurise the incoming feedwater, which reduces the external power required to raise the feedwater to an adequate pressure for desalination via the RO plant membranes. Due to the extraction of energy from the brine stream, the brine must be pumped away for disposal using a brine disposal pump.

There are a variety of options available for brine stream removal and disposal, which are detailed at 'Salt production for zero discharge system.' [Alberti et al, 2008]

3.2.1 Calculation

The general equation employed was:

Pelton Wheel BSR RO plant energy = energy to power simple (no-BSR) plant – energy recovered by Pelton Wheel + energy to remove brine from site.

The energy recovery from the Pelton Wheel is given by:

$(Vc \times Pc \times \eta_{turb})/36$

where:

V_c = volume of concentrate (m^3)

P_c= concentrate pressure (bar)

η_{turb} = efficiency of Pelton wheel turbine taken here as constant 88%. [Olga and Sallangos, 2004]

3.3 Pressure Exchanger

The Pressure Exchanger RO plant system modelled is shown below in Figure 32.

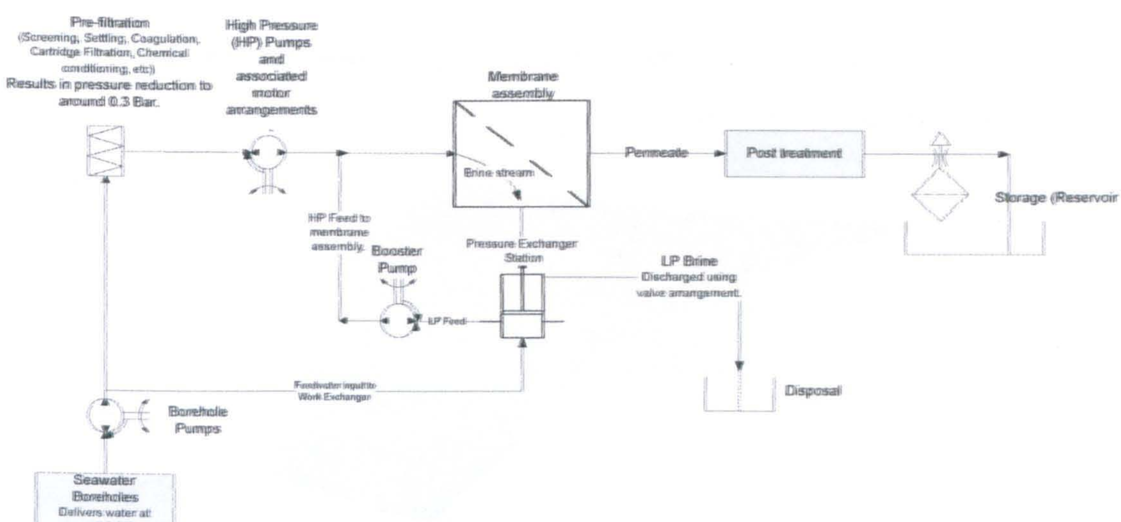

Figure 32: RO plant using Pressure Exchanger for BSR design

As shown in Figure 32 above, the Pressure Exchanger BSR RO plant uses the brine stream to pressurise a hydraulic chamber (the pressure exchanger station). This hydraulic chamber acts on a piston arrangement which, in turn, is used to partially pressurise the incoming feedwater. A booster pump then raises the now partially-pressurised feedwater to the correct pressure, to combine with the feedwater pressurised by the high pressure pump for desalination by the RO plant membranes. After pressurising the incoming feedwater, the brine stream (which is still partially pressurised) is discharged using valve arrangements as a low pressure brine stream.

3.3.1 Calculation

The general equation employed was:

> Pressure exchanger BSR RO Plant energy = Energy to produce permeate for No BSR plant - energy recovered by pressure exchanger + energy required to boost pressure of concentrate for re-application to membranes.

3.3.1.1 Booster pump power demand

The booster pump power demand was taken as:

> The appropriate proportion of the energy required to boost diverted feedwater to achieve full feed pressure, and the volume of water this boosting acts upon.

This was modelled using the following equation:

> Booster pump power = Non-BSR pressurisation power for that scenario x ((booster pressure required/ membrane feed pressure) x (volume of feedwater to be boosted/ volume of feed)).

3.4 RO Plant profiles at varying temperatures

Shown below in Figure 33 and Figure 34 are the resulting operating profiles for the Pelton Wheel and Pressure Exchanger RO plants, respectively.

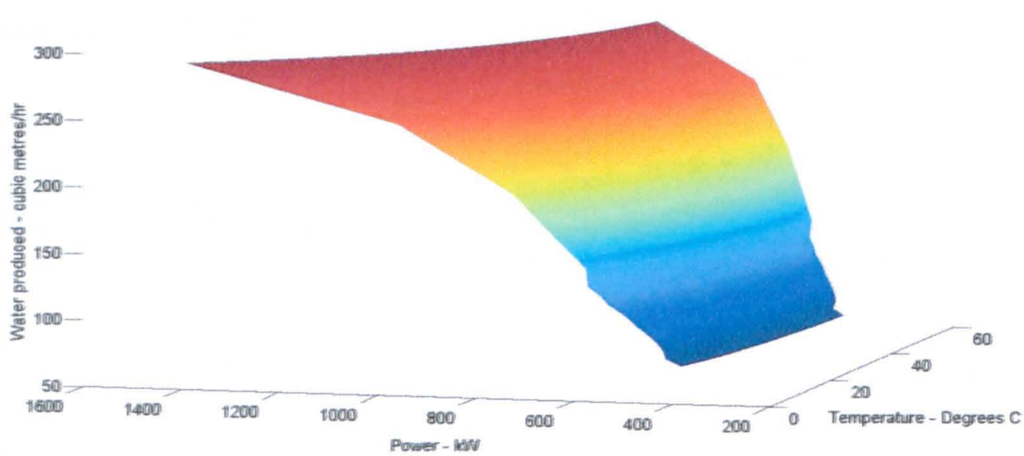

Figure 33: Pelton Wheel RO Plant water production profile at varying power and feedwater temperature

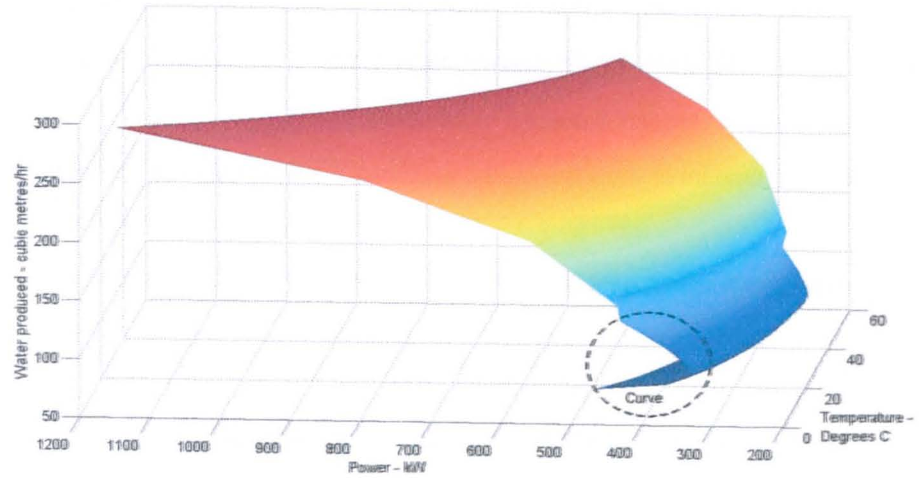

Figure 34: Pressure Exchanger RO Plant water production profile at varying power and feedwater temperature

3.4.1 Revision to Pressure Exchanger BSR profile

It is noteworthy that the initial calculation of the Pressure Exchanger profile at Figure 34 above had a curve at the bottom, which meant that at a given power level, there were two options for the volume of water that would be produced. The data for the model was modified to ensure that the lower volume water production option for each temperature was not available. This resulted in the Pressure Exchanger BSR RO plant operating profile shown below in Figure 35.

Only power settings above that required to achieve the minimum flowrate, of 92m^3/hr, were used.

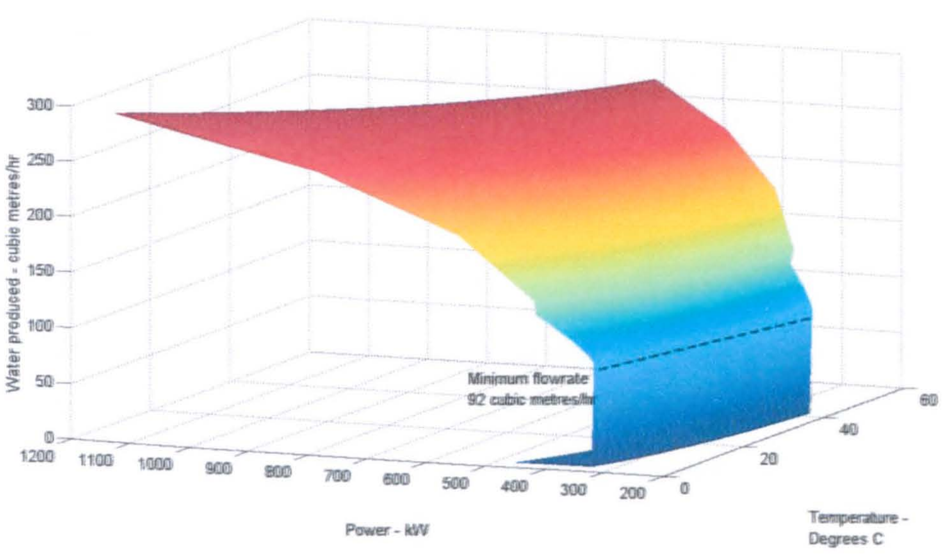

Figure 35: Revised Pressure Exchanger RO Plant water production profile at varying power and feedwater temperature

3.5 Evaluation of water produced

Following the same methodology used for the No BSR RO plant, data for each hour of the year for power available to be used by the BSR plants (and the power wasted) with corresponding feedwater temperature for each site was used to calculate the water produced.

The method used to calculate the amount of water generated was a 'for' loop in Matlab as shown below:

```
for i=1:rwr
newwater1(i) =polyval(ppolycoef(index(i),:),Pg1(i,:));
end
```

where:

Pg 1 = the power available to operate the BSR RO plant at each hour during the year.

index identifies the location of the prevailing seawater temperature for each hour of the year within the table of all available options.

ppolycoeff the a file that contains all the polynomial equations relating to each 0.01°C feedwater temperature step, from 3 – 42 °C.

i=1:rwr defines the number of times that the calculation should be conducted before stopping – in this case, 8760 times – once for each hour of the year.

i=the number of the calculation being conducted: in this case, conducted in sequence from 1 – (rwr) the max number which is 8760 (the number of hours in a year).

Polyval is the Matlab function that then evaluates the polynomial equation identified by (index (i)), making the corresponding Pg at (i) the subject.

4 Model of most reliable power source

The most reliable (non-varying) power source was taken to be conventional energy that the renewable energy sources will be compared to for technical competence.

The power demand for the BSR RO plants is shown below in Figure 36.

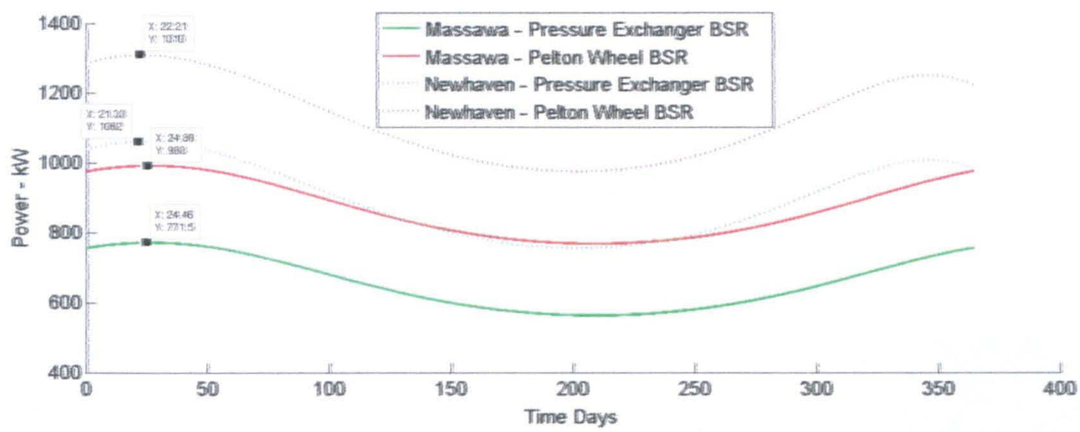

Figure 36: BSR RO plant power profiles over 1 year to maintain maximum flowrate at Massawa and Newhaven

4.1 Massawa

As shown in Figure 36 above, Massawa requires its maximum input of 993kW and 772kW at 24 days for the Pelton Wheel and Pressure Exchanger RO plants, respectively. For the purposes of this research, the plant sizes that the renewable energy was compared to were conventional plants of:

- Pelton Wheel - 1,000kW
- Pressure Exchanger – 800kW.

4.2 Newhaven

Also shown in Figure 36 above, Newhaven requires its maximum input of 1,310kW and 1,062kW at 21 and 22 days for the Pelton Wheel and Pressure Exchanger RO plants, respectively. For the purposes of this research, the plant sizes that the renewable energy was compared to were conventional plants of:

- Pelton Wheel - 1,400kW
- Pressure Exchanger – 1,100kW.

5 Supplementing power sources

The next stage in the modelling process was to hybridise the energy plant, by supplementing the primary power source with wind or wave power. This was in an attempt to maintain 24 hour RO plant daily running, as shown below in Figure 37 and Figure 38 for Massawa and Newhaven, respectively.

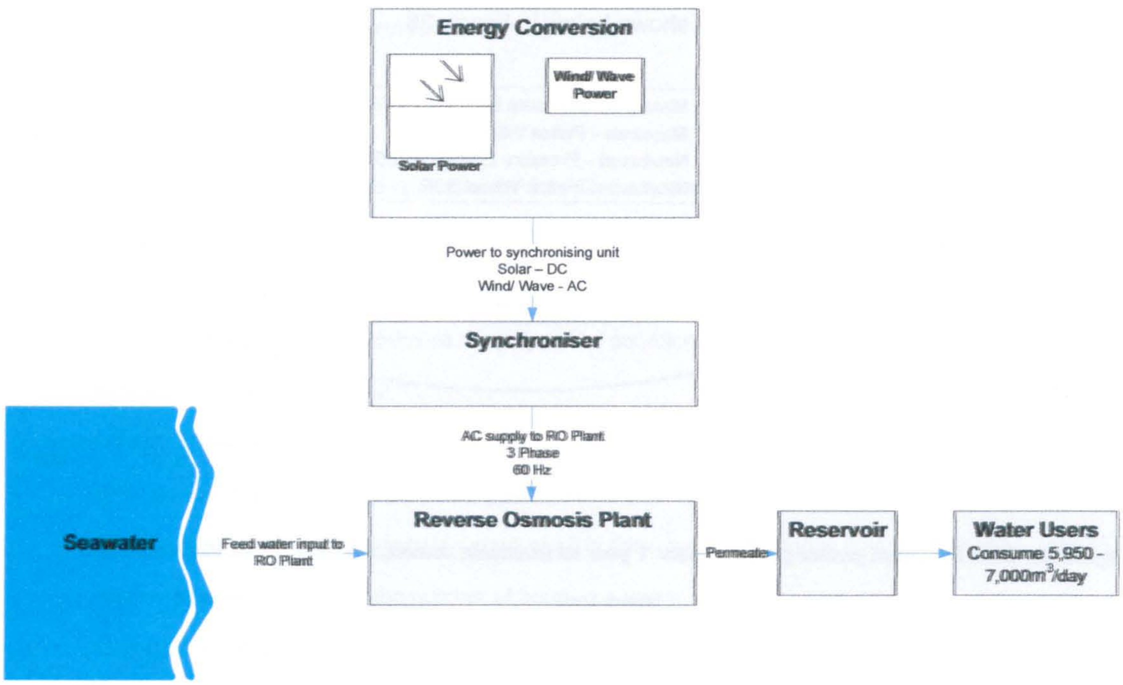

Figure 37: Hybridised Plant at Massawa

5.1 Synchronisation of Solar and Wind/ Wave Power

Modelling was carried out such that the PV cells would supply DC power, and the supplementing wind/ wave power would produce AC power, as shown in Figure 37 above. The AC from the wind/ wave devices would be converted to DC using rectifiers, and added to the DC power from the PV cells. This combined DC power would then be converted (using an inverter) to AC suitable for use by the RO plant. The efficiency of these power conversions was taken as between 90 and 95%.

5.2 Synchronisation of Tidal Current and Wind/ Wave Power

Modelling was carried out such that the SeaGen Tidal Current Turbines and the supplementing wind/ wave power devices would produce AC power as shown in Figure 38 below. The AC from the tidal current turbines and wind/ wave devices would be converted to DC using rectifiers, and combined to a single DC power source. This combined DC power source would then be converted to AC (using an inverter) suitable for use by the RO plant. The efficiency of these power conversions was taken as between 90% and 95%.

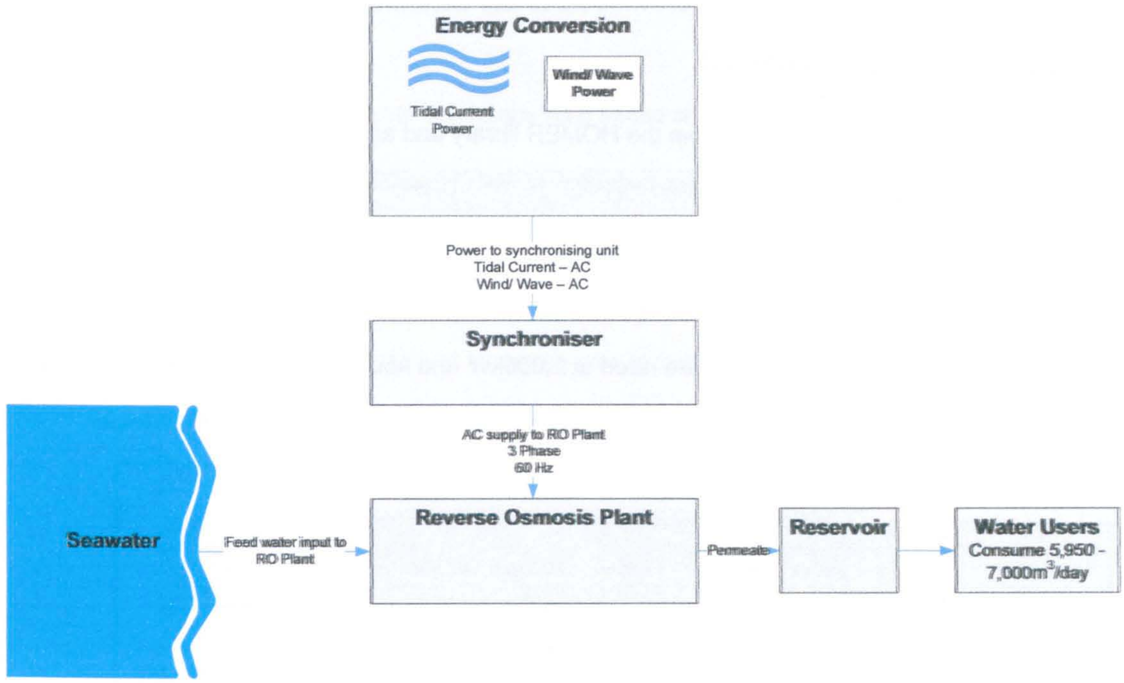

Figure 38: Hybridised Plant at Newhaven

5.3 Wind Power

The methodology for converting wind into power is quite firmly established through wind turbines. A wind turbine will deflect the wind before the wind reaches the rotor plane. This means that it is impossible to capture all of the energy in the wind using a wind turbine.

The more kinetic energy a wind turbine extracts from the wind, the more the wind will be slowed down as it passes through the blades. It follows that if all the available energy were extracted from the wind by the turbine, the air would move away with zero speed, i.e. the air could not physically leave the turbine. In that case, no energy would be extracted at all, since all of the following air would also be prevented from entering the rotor of the turbine.

Taking the other extreme case, the wind could pass through the turbine without being disturbed, and the turbine would not extract any energy from the wind. Betz's Law provides the most efficient level for converting the energy in the wind to useful mechanical energy between these two extremes.

5.3.1 Betz's Law

Betz's law (or the Lanchester–Betz–Joukowsky limit) [Gijs, 2007][27] states that a maximum of 16/27 (or 59%) of the kinetic energy in the wind can be converted to mechanical energy using a wind turbine.

5.3.2 Wind turbines to be employed

The following wind turbines were selected from the HOMER library and assessed:

- The WES 30, and
- The Fuhrlander 250.

These turbines are rated at 260 and 300 watt respectively.

For efficiency, the current crop of machines are rated at 2,000kW and above, so the operating profiles of the WES 30 and Fuhrlander 250 were scaled-up to reflect this trend, as shown below in Figure 39.

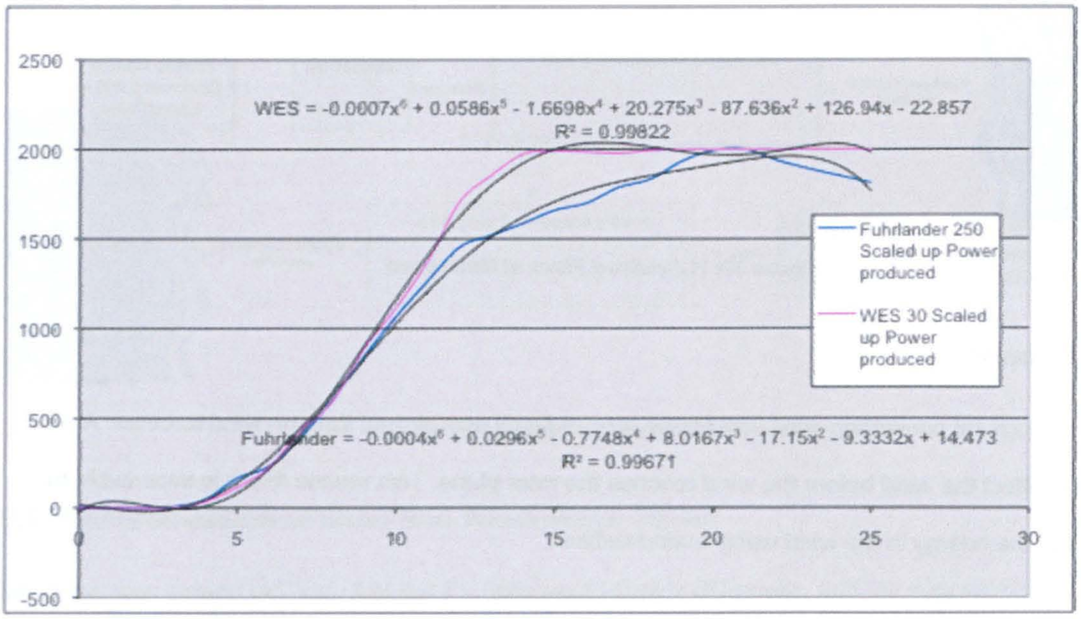

Figure 39: Scaled up WES 30 and Fuhrlander 250 operating profiles

The next step was to assess which of the options should be used as part of the modelling for the present research.

[27] The British scientist Lanchester derived the same maximum in 1915, some five years before Betz who is credited with its discovery in 1920. A study of early Russian publications on rotor aerodynamics now shows that the Russian aerodynamic school also produced the same result; its leader Joukowsky derived the maximum efficiency for an ideal wind turbine in the same year as Betz. Consequently, in order to honour all, this ideal efficiency should be named the 'Lanchester-Betz-Joukowsky limit' in scientific writing. The well-established and convenient name Betz limit is generally accepted as an abbreviation of this full name.

5.3.3 Wind Resource available at each site

5.3.3.1 Newhaven

The wind resource available at Newhaven was taken from the UK wind speed database NOABL[28], and is shown below in Table 6.

Table 6: Average wind speed at Newhaven

Height of reading (m)	Mean wind speed (m/s)
10	6
25	6.7

5.3.3.2 Massawa

The monthly average wind speed data at Massawa was taken from local weather reports[29], and is presented below in Table 7.

Table 7: Average wind speed at Massawa

Data	Mean wind speed at 10m height (m/s)
Jan	3.576
Feb	3.576
Mar	5.812
Apr	5.812
May	5.812
Jun	5.812
Jul	4.917
Aug	5.364
Sep	4.917
Oct	5.364
Nov	5.364
Dec	5.364
Annual Average	5.141

This data was then applied to HOMER to derive the wind speed for each hour of the year, shown below in Figure 40.

[28]Taken from http://www.rensmart.com/Weather/BERR [Last viewed on 7 August 2011]. The data in this database is the result of an air flow model that estimates the effect of topography on wind speed. Newhaven data was based on the following coordinates 50.78076029964647 Lat: 0.0473785400390625 long.

[29] Average monthly data is based on the average of data over 4 years. Coordinates for Massawa are 15 36' 35" Lat: 39 27' 00" Long taken from http://www.weatherreports.com/Eritrea/Massawa/averages.html [Last viewed on 7 August 2011].

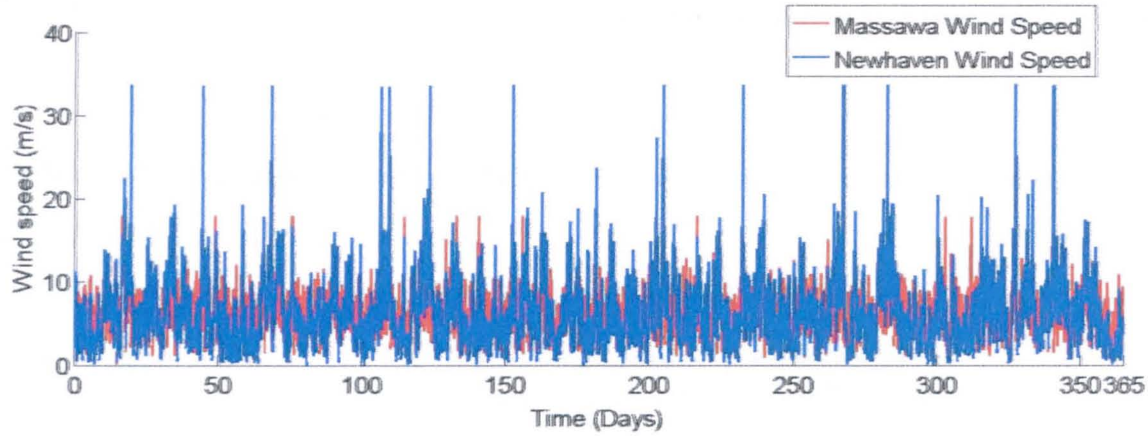

Figure 40: Wind speeds at Massawa and Newhaven over 1 year

Based on the operating profiles of the two scaled-up wind turbines, it was decided that the scaled-up Fuhrlander 250 operating profile should be employed for this modelling exercise, as it was more effective at delivering power from the prevailing wind speeds at each site.

This is illustrated in Figure 41 and Figure 42 for Newhaven and Massawa, respectively.

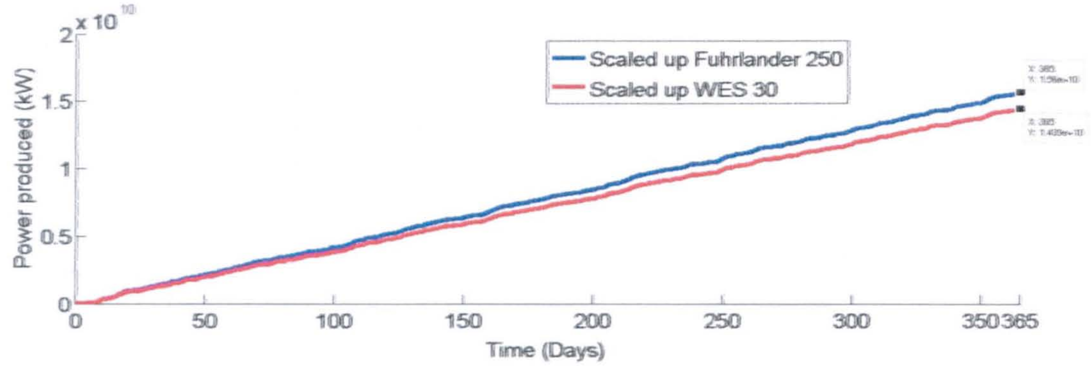

Figure 41: Single scaled-up wind turbine performance at Newhaven over 1 year

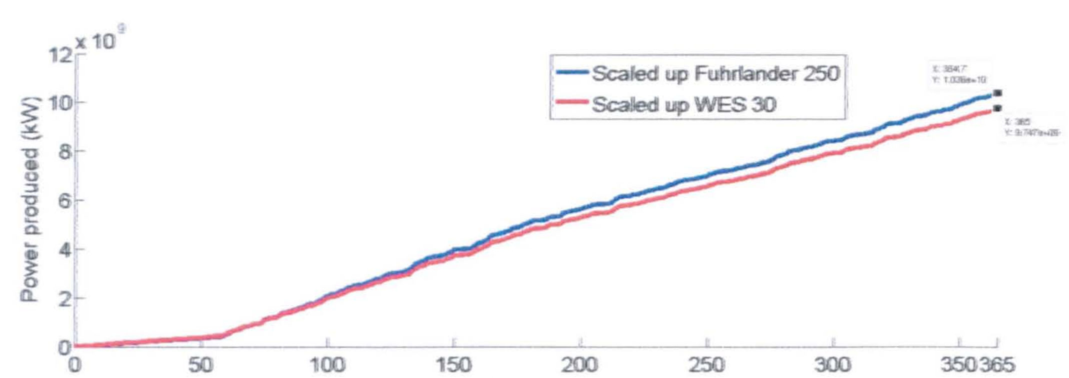

Figure 42: Single scaled-up wind turbine performance at Massawa over 1 year

It is noteworthy that although the scaled-up WES 30 generates more power for more of the time than the scaled-up Fuhrlander, as shown in Figure 39 above, the scaled-up Fuhrlander generates more power at wind speeds of between 3 and 6m/s. For the wind profile using a Weilbull distribution (k) value = 2, more than one third of the total wind speeds for the year occur between 3 and 6m/s, which results in the scaled-up Fuhrlander out-performing the apparently more effective scaled-up WES 30, over the course of the year.

5.4 Wave Power

5.4.1 Wave power delivery devices

Three wave power devices were considered, which each represent a version of the main wave device options:

- Pelamis – Attenuators[30]
- Wave Dragon – Terminators[31]
- Archimedes Wave Swing – Point absorbers[32].

The operating profiles for each of these wave devices are shown below in Figure 43 - Figure 45 inclusive based on the 'Variability of UK marine resources - An assessment of the variability characteristics of the UK's wave and tidal current power resources and their implications for large scale development scenarios' [Environmental Change Institute, 2005][33].

[30] An Attenuator is a floating device which works parallel to the wave direction, and effectively rides the waves. Movements along its length can be selectively constrained to produce energy. It has a lower area parallel to the waves in comparison to a Terminator (described below), so the device experiences lower forces.

[31] A Terminator device extends perpendicular to the direction of wave travel, and captures or reflects the power of the wave.

[32] A Point Absorber is a floating structure which absorbs energy in all directions through its movements at/near the water surface.

[33] The 'transform matrices' at pages 32 and 33 were used to provide the link between the ambient wave conditions and the anticipated output of the wave power device, with the estimated power output determined from the average wave period and height over a one-hour period.

5.4.1.1 Pelamis

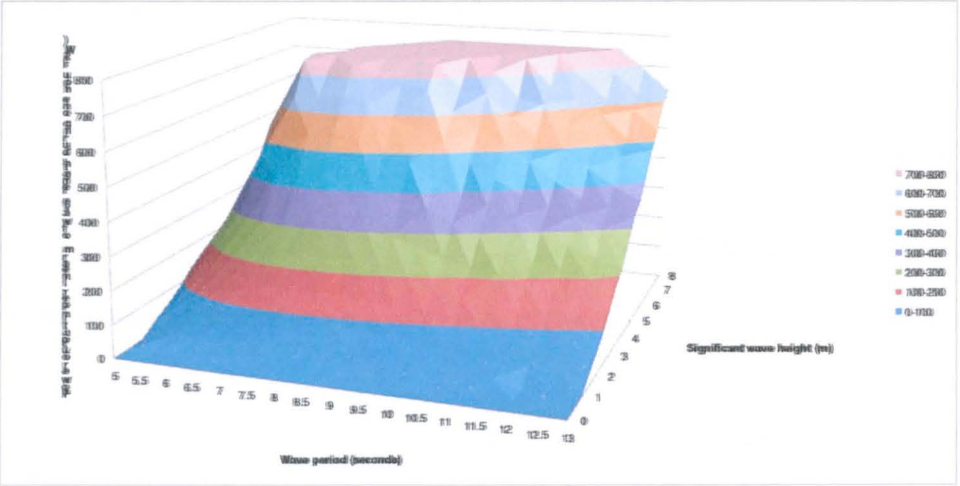

Figure 43: Pelamis power transformation matrix (generic performance)

5.4.1.2 Wave Dragon

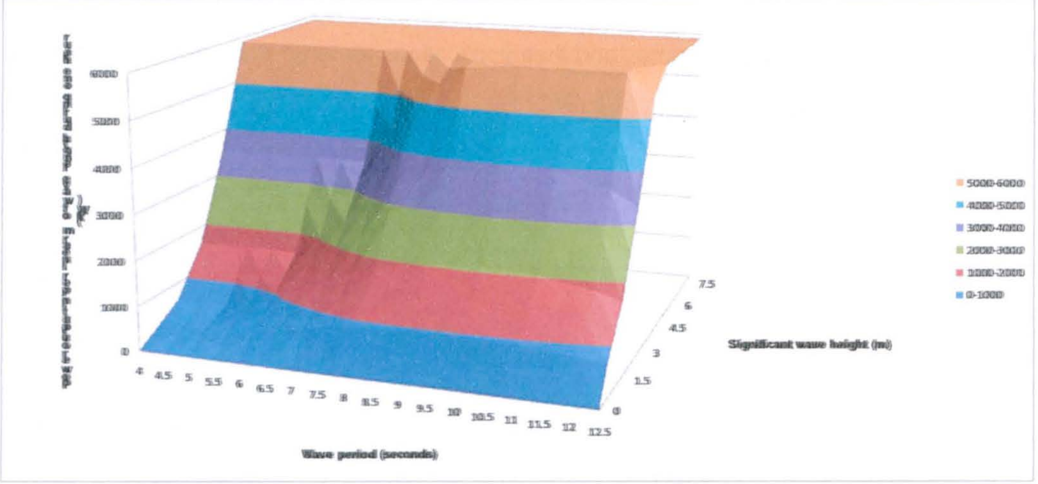

Figure 44: Wave dragon power transformation matrix (optimised for high average wave conditions).

5.4.1.3 Archimedes wave swing

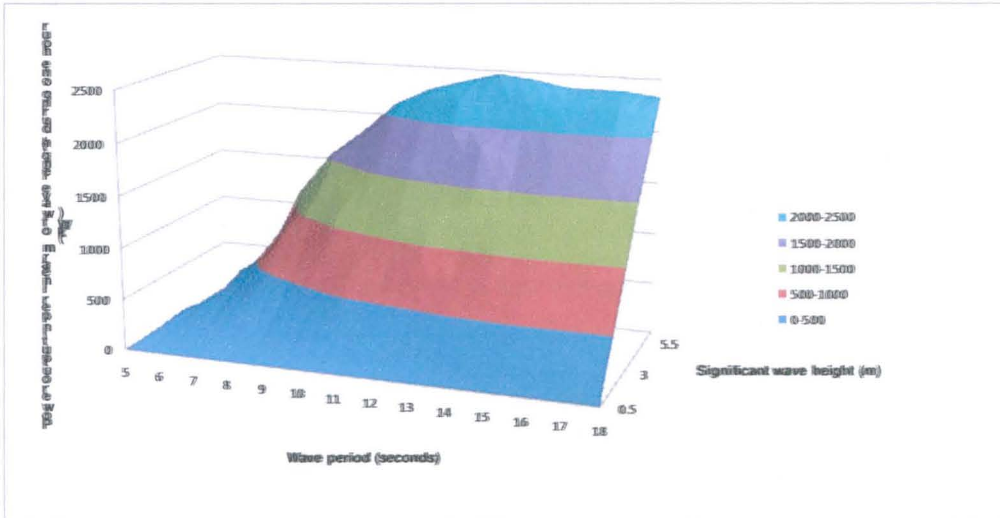

Figure 45: Archimedes wave swing power transformation matrix (unrestricted)

5.4.2 Wave period to be modelled

5.4.2.1 Newhaven

Based on the paper 'Prediction of nearshore wave energy distribution by analysis of numerical wave model output, East Sussex coastline, UK' from the Geological Society [Mitchell and Pope, 2004], it was concluded that the waves at Newhaven act with a wave period of 7 seconds, which allowed the comparison shown below in Figure 46 to be made.

5.4.2.2 Massawa

The wave period of 7 seconds was also applicable at Massawa, based on a mean significant wave period of 6.7 sec calculated in 'Statistical Wave Parameters Offshore Jeddah Coast' [Abdelrahman, 1995].

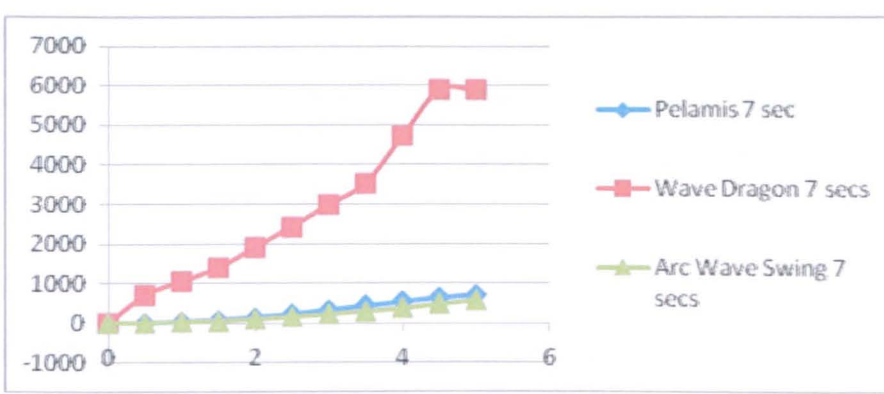

Figure 46: Power delivery from each device at varying wave heights, at constant wave period of 7secs

From this, it is evident that the wave dragon is by far the most effective device for power production on a power conversion per meterage of wave basis, and this was thus adopted as the device for modelling in this research.

5.4.3 The Wave Dragon

The Wave Dragon (illustrated below in Figure 47) is an 'overtopping' wave energy converter, and is floated slack-moored, to allow it to move in the direction of the prevailing waves.

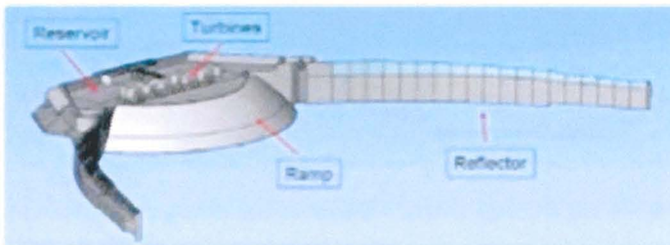

Figure 47: Wave Dragon wave power conversion device

The principle of operation of the wave dragon device is illustrated below[34] in Figure 48.

-

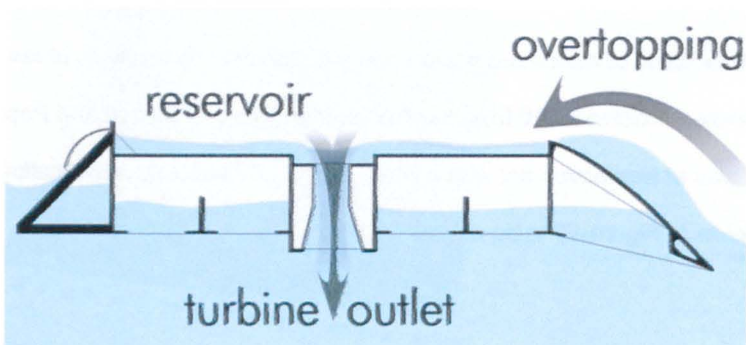

Figure 48: The principle of the Wave Dragon technology

The Wave Dragon works by facing its outstretched collector arms towards the oncoming waves and concentrating the wave front towards the ramp at the front of the structure[35]. As shown by Figure 48 above, energy is captured by waves running up the ramp and overtopping the crest into a reservoir. This water, stored in the reservoir, at a higher level than the sea, is returned through low- head turbines powering electrical generators producing AC power.

---

[34] Source of diagram: http://www.brighthub.com/engineering/marine/articles/55295/image/58398/ [Last viewed on 7 August 2011].

[35] This focusing increases the wave height at the ramp, which in turn acts like a beach and causes the waves to overtop the device without breaking (and therefore without losing their potential energy) into the reservoir behind it.

The first Wave Dragon prototype connected to the grid is currently deployed in Denmark[36].

The power production profile for the Wave Dragon was taken as shown below in Figure 49 and a polynomial curve fitted to it, where:

x = wave height.

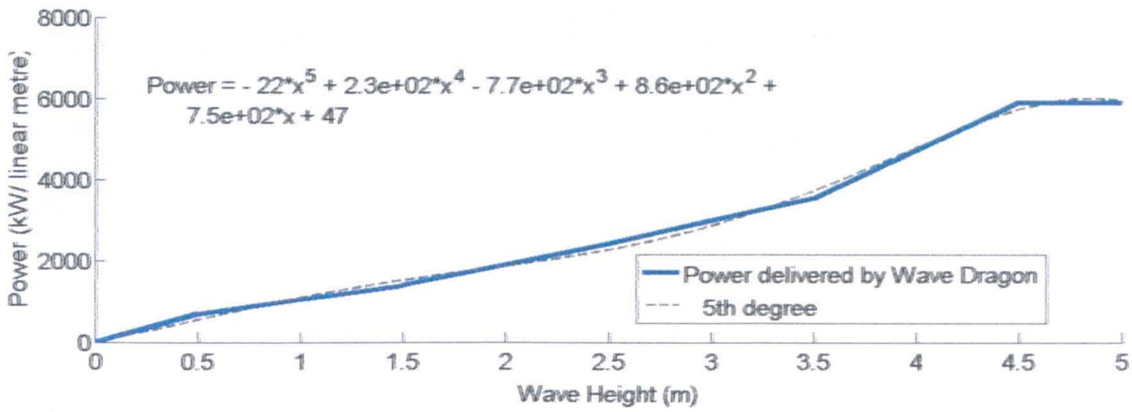

Figure 49: Power output from Wave Dragon at 7-second significant wave period.

5.4.3.1 Wave height

The average monthly wave height data for Massawa and Newhaven from ARGOSS[37] was employed, and these are shown below in Tables 8 and 9, respectively.

---

[36] The 20kW prototype is located at Nissum Bredning in Denmark. Detail of this prototype and the wave dragon device in general are available at http://www.wavedragon.net/ [Last viewed on 7 August 2011].

[37] Tables were kindly provided by Feddo Vollema of ARGOSS. See the website at http://www.argoss.nl/ for greater detail of the organisation's activities. [Last viewed on 7 August 2011].

Table 8: Average wave heights near Massawa

Monthly distribution of wave height (m)

lower	upper	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.2	0	0.074	0.762	2.13	7.325	2.94	3.898	4.077	6.227	9.334	1.065	0
0.2	0.4	3.386	4.813	6.944	14.769	27.666	15.81	18.705	17.339	28.009	35.551	14.375	6.676
0.4	0.6	20.566	21.783	21.729	29.761	29.525	25.486	27.397	28.538	29.954	29.727	31.134	24.233
0.6	0.8	27.932	26.105	25.375	22.361	16.465	20.602	22.043	24.843	17.245	13.732	28.611	30.847
0.8	1	21.114	17.829	17.047	14.19	8.625	15.509	14.83	12.881	9.213	7.728	12.755	16.42
1	1.2	11.091	11.321	11.514	8.565	4.749	9.051	7.079	5.922	4.537	2.923	5.995	11.47
1.2	1.4	6.955	8.36	7.191	5.231	3.024	5.186	3.383	3.131	2.325	0.582	3.032	4.956
1.4	1.6	4.908	4.298	4.122	1.568	1.322	3.773	1.368	1.232	1.528	0.322	1.713	2.621
1.6	1.8	2.455	2.529	2.061	1.204	0.851	1.273	0.986	0.896	0.532	0	0.671	1.478
1.8	2	1.159	1.375	0.874	0.44	0.326	0.231	0.112	0.262	0.394	0	0.509	0.665
2	2.2	0.295	0.663	0.314	0.069	0.112	0.133	0	0.09	0.046	0	0.139	0.246
2.2	2.4	0.114	0.27	0.022	0.023	0	0	0	0	0	0	0	0.157
2.4	2.6	0.023	0.172	0.045	0	0	0	0	0	0	0	0	0.045
2.6	2.8	0	0.296	0	0	0	0	0	0	0	0	0	0.09
2.8	3	0	0.172	0	0	0	0	0	0	0	0	0	0.045
3	3.2	0	0.049	0	0	0	0	0	0	0	0	0	0.022
3.2	3.4	0	0	0	0	0	0	0	0	0	0	0	0
total		100	100	100	100	100	100	100	100	100	100	100	100

Your choices :

Model output point is 16° 30'N, 39° 45'E
Season is all year
Variable is wave height (m)
Data source is wavemodel
Results are based on 52536 model records

Table 9: Average wave heights near Newhaven

Monthly distribution of wave height (m)

lower	upper	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.2	0	0	0.134	0.185	0.56	0.945	0.157	1.075	0.741	0	0.116	0
0.2	0.4	0.881	1.375	2.576	3.657	4.525	8.074	6.717	5.663	6.088	2.495	1.458	0.56
0.4	0.6	2.016	4.42	7.056	9.977	14.83	16.819	20.161	23.208	13.75	6.788	5.324	2.352
0.6	0.8	5.456	9.332	10.613	15.88	18.1	20.654	21.309	21.617	16.723	11.246	10.324	7.953
0.8	1	8.087	12.844	11.85	18.056	16.644	16.958	15.372	15.547	16.574	15.075	10.995	12.087
1	1.2	8.132	11.395	11.537	14.338	11.918	11.644	11.156	9.319	11.597	11.353	10.37	11.649
1.2	1.4	8.333	7.981	10.595	11.134	8.289	8.009	7.482	7.28	8.912	9.453	9.074	7.957
1.4	1.6	8.659	7.957	10.17	6.088	6.564	4.375	5.299	5.13	6.348	7.594	8.102	6.922
1.6	1.8	8.02	8.03	8.087	5.069	5.852	3.009	4.256	3.271	4.884	7.146	6.852	6.743
1.8	2	7.124	5.329	6.496	4.213	4.189	1.991	1.527	2.419	3.935	6.496	6.181	6.183
2	2.2	7.079	4.862	4.592	2.685	2.621	1.181	1.38	1.77	3.213	4.906	6.968	5.735
2.2	2.4	5.608	5.108	3.535	2.195	2.039	0.926	1.232	0.784	2.454	4.055	5.324	5.533
2.4	2.6	4.816	3.929	3.047	1.505	1.098	0.44	0.806	0.582	1.753	3.091	4.375	4.816
2.6	2.8	5.108	3.684	2.173	1.551	1.058	0.417	0.672	0.314	1.273	2.464	3.218	4.323
2.8	3	3.898	2.431	1.535	0.787	0.672	0.069	0.493	0.269	0.943	1.613	2.824	2.845
3	3.2	3.383	2.161	1.856	0.995	0.538	0.139	0.224	0.358	0.37	1.635	1.898	2.464
3.2	3.4	3.002	2.382	1.501	0.301	0.179	0.046	0.09	0.157	0.185	0.986	1.875	2.531
3.4	3.6	2.258	1.768	0.951	0.231	0.067	0.069	0.045	0.09	0.115	0.941	1.343	1.972
3.6	3.8	2.106	1.351	0.717	0.162	0.067	0.046	0.022	0.09	0.115	0.717	1.065	1.344
3.8	4	1.747	1.13	0.538	0.093	0.022	0.046	0	0.022	0.023	0.493	0.671	1.058
4	4.2	1.299	0.884	0.224	0.116	0.045	0	0	0.045	0	0.291	0.486	1.299
4.2	4.4	0.735	0.246	0.134	0.023	0.022	0.023	0	0	0	0.246	0.347	0.986
4.4	4.6	0.515	0.442	0.134	0.046	0.022	0	0	0	0	0.291	0.208	0.874
4.6	4.8	0.493	0.295	0.067	0.046	0	0.023	0	0	0	0.202	0.116	0.56
4.8	5	0.449	0.295	0.157	0	0	0.023	0	0	0	0.09	0.162	0.336
5	5.2	0.202	0.147	0	0.046	0	0.023	0	0	0	0.067	0.046	0.251
5.2	5.4	0.045	0.098	0	0.046	0	0	0	0	0	0.045	0.023	0.314
5.4	5.6	0.067	0.049	0	0.023	0	0	0	0	0	0.112	0.116	0.09
5.6	5.8	0.067	0.074	0.022	0.046	0	0	0	0	0	0.045	0.023	0.022
5.8	6	0	0	0.022	0	0	0	0	0	0	0.09	0.023	0.022
6	6.2	0	0	0	0	0	0	0	0	0	0.067	0	0.022
6.2	6.4	0.067	0	0	0	0	0	0	0	0	0.09	0	0.045
6.4	6.6	0	0	0	0	0	0	0	0	0	0.067	0.023	0
6.6	6.8	0	0	0.022	0	0	0	0	0	0	0.022	0	0.022
6.8	7	0	0	0	0	0	0	0	0	0	0	0	0
7	7.2	0	0	0.022	0	0	0	0	0	0	0.022	0	0
7.2	7.4	0.022	0	0.022	0	0	0	0	0	0	0	0	0
7.4	7.6	0	0	0	0	0	0	0	0	0	0	0	0
7.6	7.8	0	0	0	0	0	0	0	0	0	0	0	0
7.8	8	0	0	0	0	0	0	0	0	0	0	0	0
8	8.2	0.022	0	0	0	0	0	0	0	0	0	0	0
8.2	8.4	0	0	0	0	0	0	0	0	0	0	0	0
total		100	100	100	100	100	100	100	100	100	100	100	100

Your choices :

Model output point is 50° 30'N, 0° 15'W
Season is all year
Variable is wave height (m)
Data source is wave model
Results are based on 52608 model records

The average values, highlighted in red, were employed as the wave height.

Shown below in Figure 50 are the power output values for Massawa and Newhaven for their average wave heights.

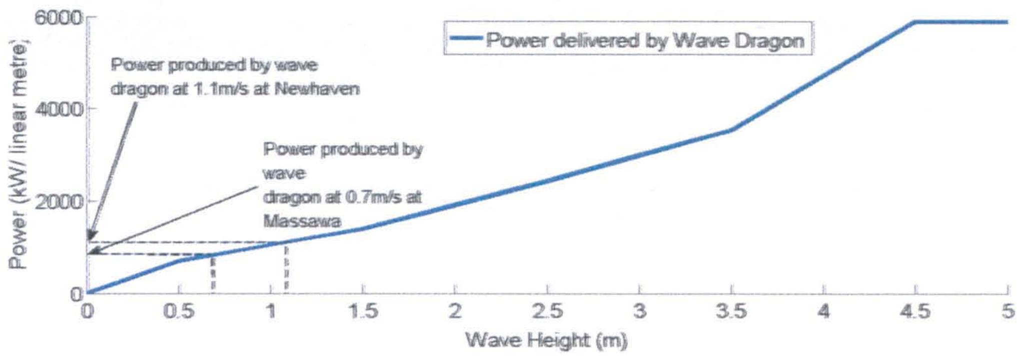

Figure 50: Power output from Wave Dragon at 7-second significant wave period with average wave heights at Massawa and Newhaven.

As can be seen from Figure 50 above, the average wave heights employed mean that the Wave Dragon device is only delivering (at best) around 1/6th of its potential power output.

5.4.3.2 Power produced by Wave Dragon device

Based on the polynomial and wave heights provided, the power produced by the Wave Dragon from 1m of wave front, was derived. The profiles for Massawa and Newhaven are shown below in Figure 51 and Figure 52, respectively, with the maximum values achieved during the year at each site.

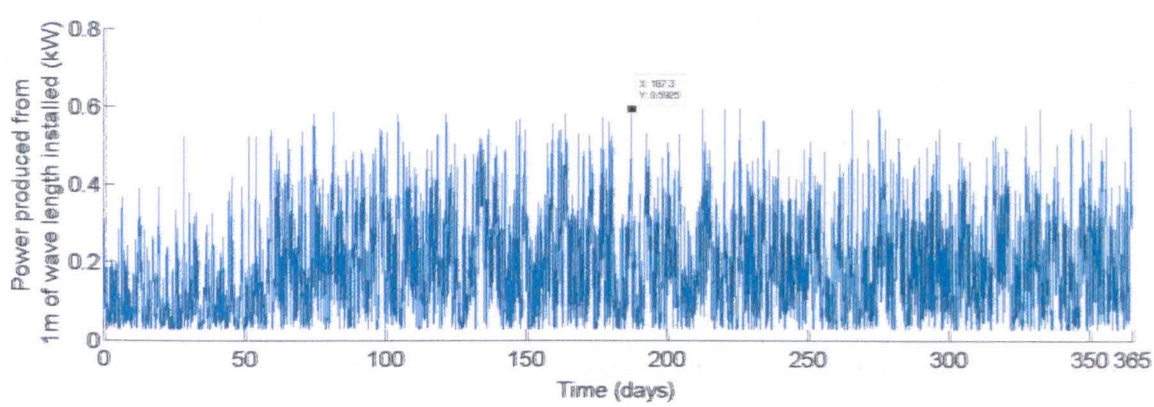

Figure 51: Power produced by 1m of Wave Dragon at Massawa during 1 year.

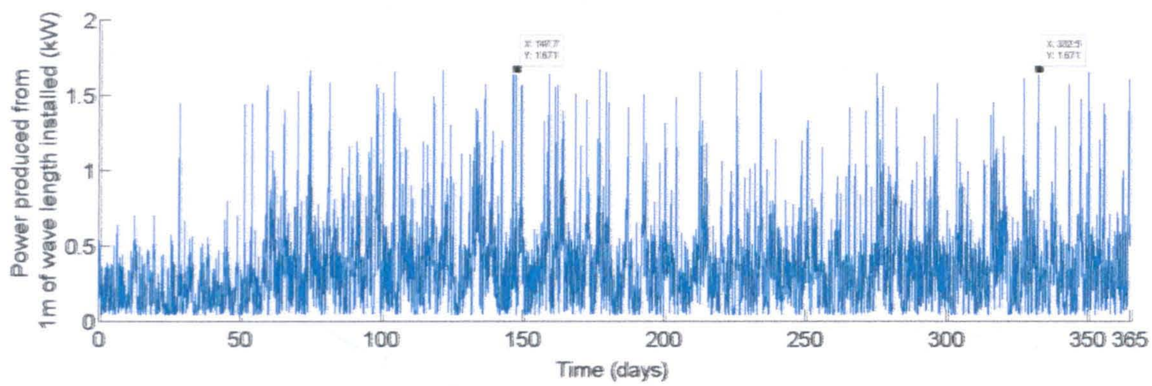

Figure 52: Power produced by 1m of Wave Dragon at Newhaven during 1 year.

5.4.3.3 Modelling of wave power.

5.4.3.3.1 Assumptions

For the purposes of this research, it was assumed that:

- The Wave Dragon device employed is a 95kW device with a wave front capture length of 57m[38], based on analysis of the Wave Dragon Devices available[39].
- The 'slack mooring' employed by the Wave Dragon allows it to capture the energy from the prevailing wave front from any direction, and
- The wave dragon devices can operate effectively in the water depths available at Massawa[40] and Newhaven[41] – maximum working depth in excess of 6.0m[42].

The maximum power delivered at each site during the course of the year (as shown in Figure 51 and Figure 52) is as follows:

- Massawa 0.5925kW/m
- Newhaven 1.671kW/m.

---

[38] When the figures were interpolated for 95kW, it was concluded that with maximum output at 5m wave heights, the wave length captured by each wave dragon device was 57m, if the device were to achieve the rated output.. Feedback on this assumption was requested from the author of the text used to derive the figures, but was not received.

[39] Wave Dragon web page showing devices available
http://www.wavedragon.net/index.php?option=com_content&task=view&id=7&Itemid=7 [Last viewed on 7 August 2011].

[40] 'Red Sea overview page', at http://www.emecs.or.jp/guidebook/eng/pdf/16redsea.pdf [Last viewed on 7 August 2011].

[41] Admiralty Survey. 2009. http://www.ukho.gov.uk/AboutUs/Documents/2009/DWRT%20Deep%20Water%20Route.pdf
[Last viewed on 7 August 2011].

[42] The Straits of Dover in English Channel (near Newhaven) have a water depth in excess of 30m.
There is a deep trench that stretches from north to south for almost the entire area of the Red Sea. The deepest region lies between 14 N and 28 N, with a maximum depth of 2,920 m. The minimum depth is between 55 - 73m and the average depth is over 500m. Source:

The power required, and the numbers of Wave Dragon devices used at each site for each of the RO plant types under consideration, is shown below in Table 10.

Table 10: Power delivered at each site and scaling employed.

Location and Type of RO plant.	Power req'd (MW)	Wave front required (km)	No. of 95kW Wave Dragon devices required, based on each device having a wave capture length of 57m.	No of Wave Dragon devices installed to take account of synchronisation losses.	Conversion efficiency (%)	Actual Wave Dragon power supplied (MW)
New_No_BSR	3.4	2.03	35	38	93.9	3.61
Mass_No_BSR	2.4	4.05	71.1	75	94.8	7.13
New_PW	1.4	0.84	14.7	16	91.9	1.52
New_PX	1.1	0.66	11.5	13	88.8	1.24
Mass_PW	1.0	1.69	29.6	32	92.5	3.04
Mass_PX	0.8	1.35	23.7	25	94.7	2.38

6 Energy Storage

It soon became clear from the energy use profile of the RO plants being modelled, that each type of renewable energy plant (hybridised and non-hybridised) had varying amounts of energy that was wasted.

This came in two distinct categories, as described in the following text, and shown graphically (using a simple solar day profile) in Figure 53 and Figure 54 below:

- Energy wasted during start-up and after shut-down, and;
- Excess energy above that required to achieve maximum flow, as well as that below the power level to achieve minimum RO plant flow rate.

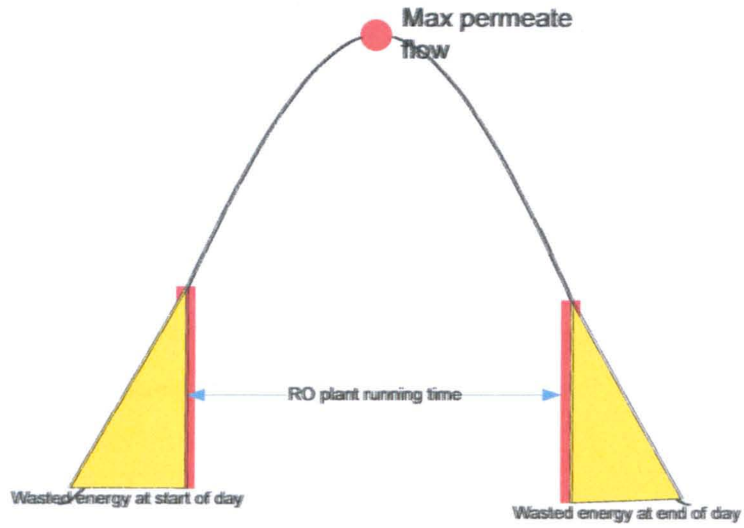

Figure 53: Energy wasted at start and end of operation

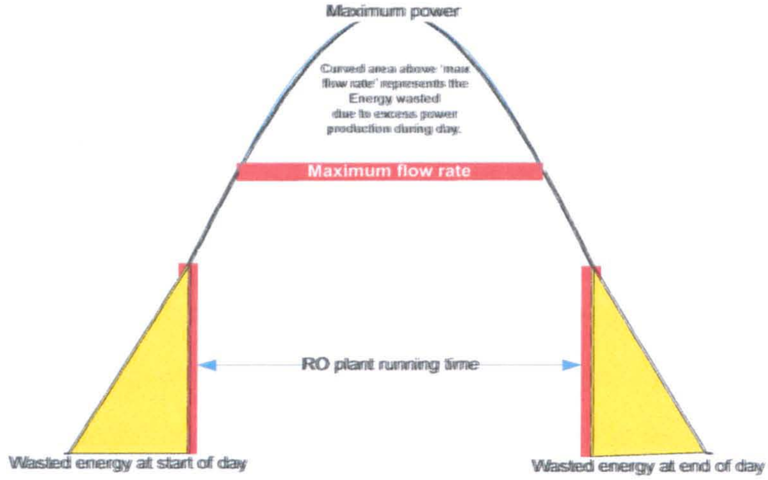

Figure 54: Energy wasted at start, end, and during RO plant operation

The following text describes how the wasted energy was captured, and reapplied to be used by the RO plant to maintain the maximum flowrate.

6.1 No energy wasted during RO plant running

Energy was wasted during start-up and after shut-down. The energy available during start-up can be captured and used to extend the RO plant running time at maximum flow rate, as illustrated below in Figure 55.

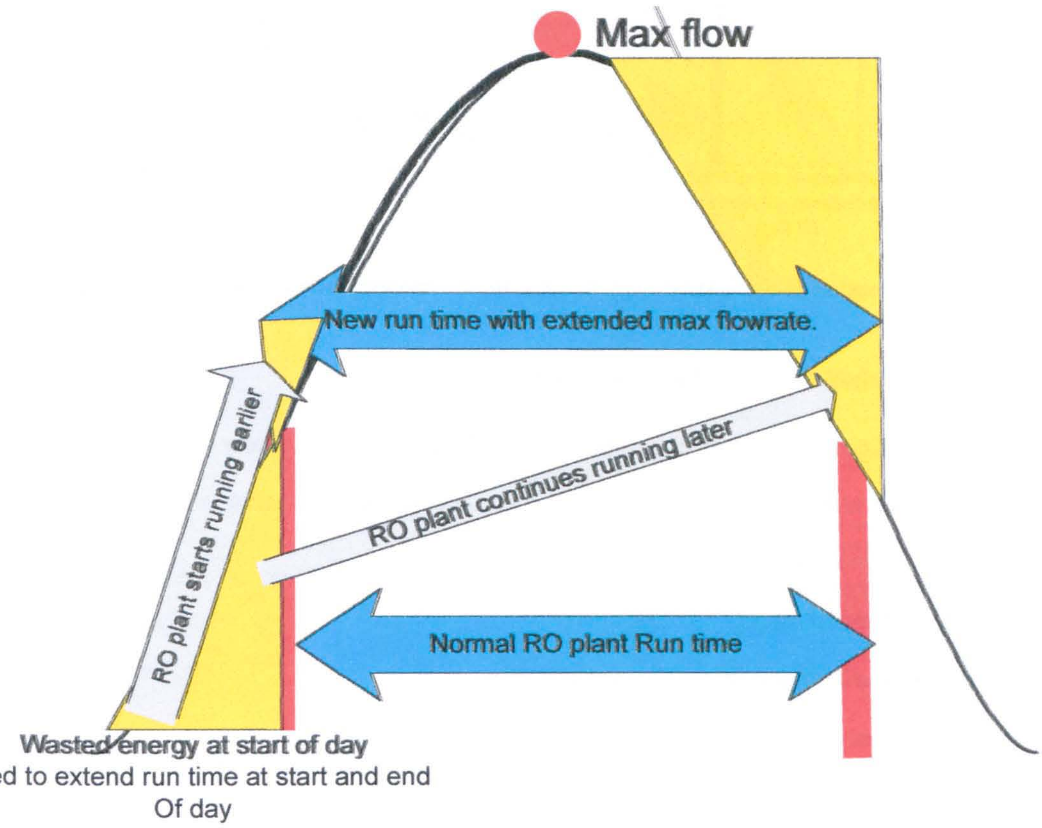

Figure 55: Application of captured energy to increase the running time at maintain maximum flow rate (not to scale)

6.2 Energy wasted before, during and after RO plant running

Alternatively, the energy wasted at the beginning and during RO plant running can be used to extend the RO plant running time at a reduced maximum flow rate, as illustrated below in Figure 56.

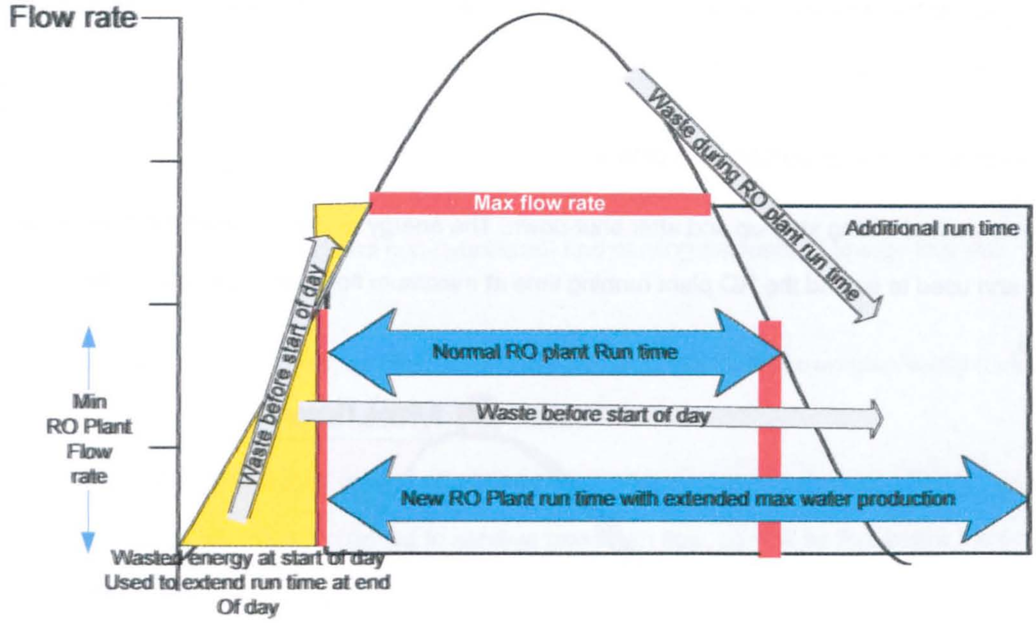

Figure 56: Application of captured energy to increase the running time of the RO plant (not to scale)

6.3 Types of energy storage systems available

'Projections of levelised cost benefit of grid-scale energy storage options' [Doty et al, 2010] identifies several options that do not use conventional power, that are available for storage of the captured energy on a 'grid scale'. These include:

- Pumped hydro storage;
- Underground Pumped Hydro Storage (UPHS);
- Hydrogen Fuel Cells;
- Batteries;
- Advanced adiabatic compressed air energy storage (AA-CAES);
- Flywheels;
- Ultra capacitors, and;
- Superconducting magnetic energy storage (SMES).

The following text presents a brief overview of each of these technologies. A more detailed description of each of them, and other energy storage methodologies, is available at 'Prospects for Large-Scale Energy Storage in Decarbonised Power Grids' [OECD/IEA, 2009].

6.3.1 Pumped hydro storage

Pumped hydro storage requires two reservoirs at different altitudes. When the water is released from the upper reservoir, energy is generated by the downflow which is directed through high-pressure shafts, linked to turbines. In turn, the turbines power generators to create electricity.

Water is pumped back to the upper reservoir by linking a pump shaft to the turbine shaft, using a motor to drive the pump, as shown below in Figure 57.

The power for the motor is normally provided during periods of excess power production.

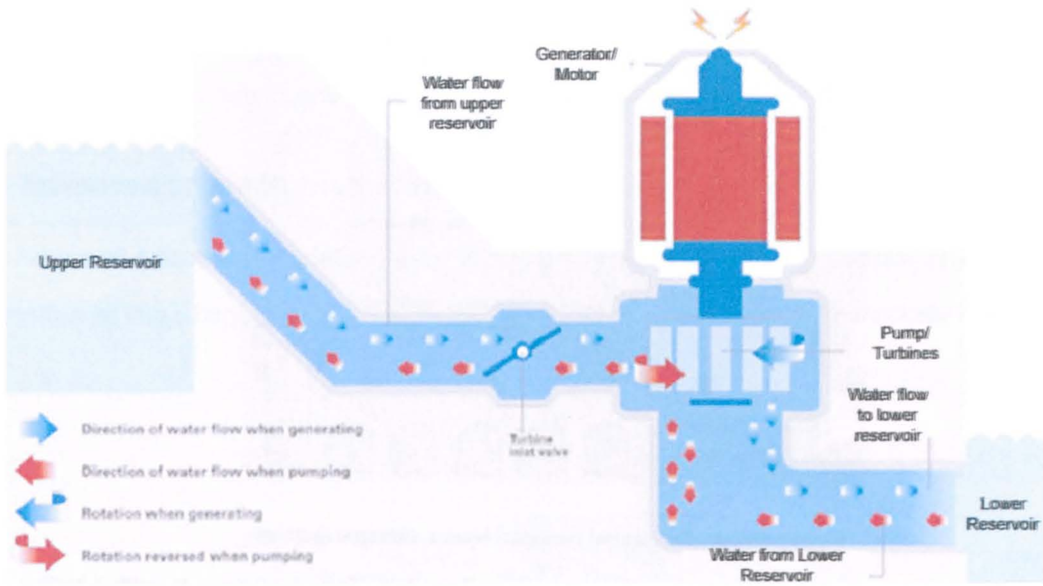

Figure 57: Pumped hydro storage system

6.3.2 Underground Pumped Hydro Storage (UPHS)

The need for a significant height difference between the two reservoirs, and extensive excavation for the water-carrying galleries for pumped hydro storage, limits the application of this technology.

To overcome these limitations, the concept of Underground Pumped Hydro Storage (UPHS) was proposed by Pierre Couture, who also invented the modern wheel motor [Green Transport and Energy, 2009]. This avoids the large excavation for the galleries associated with pumped hydro storage. Pierre Couture recommended digging a well around two metres in diameter and three kilometres deep, as shown below in Figure 58.

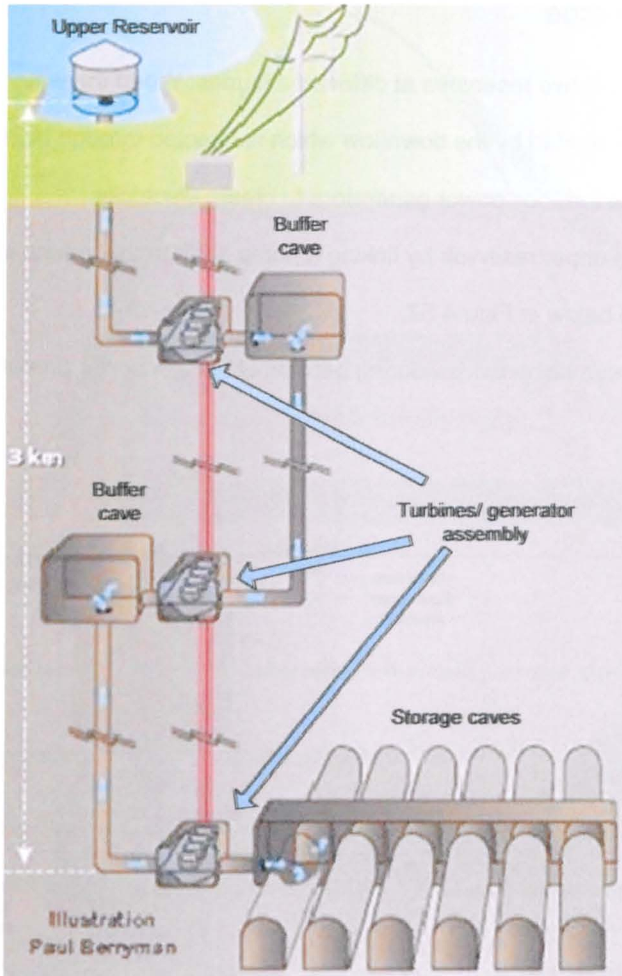

Figure 58: Underground pumped hydro storage system

Turbines that can be reversed and also act as pumps, are placed at kilometre intervals, with a buffer cave behind each group of turbine-generator assembly.

The system then operates as a normal pumped hydro storage system in that:

- The turbines power the generators to create electricity when water flows down to the storage caves.
- Water is pumped back to the upper reservoir, using the reversible turbines acting as pumps, using power provided during periods of excess production.

6.3.3 Hydrogen Fuel Cells

A hydrogen fuel cell is a device that converts the chemical energy from hydrogen into electricity through a chemical reaction. Hydrogen fuel cells differ from batteries in that they require a constant source of fuel (oxygen and hydrogen) to operate, but will produce electricity continuously as long as the fuel is supplied.

6.3.4 Batteries

A battery is a device that converts stored chemical energy directly into electrical energy. A battery consists of a number of voltaic cells, and each voltaic cell is made up of two half cells. One half-cell includes electrolyte and the electrode to which anions (negatively- charged ions) migrate, i.e. the anode, or negative electrode; the other half-cell includes electrolyte and the electrode to which cations (positively-charged ions) migrate, i.e. the cathode, or positive electrode.

The type considered by 'Projections of levelised cost benefit of grid-scale energy storage options' to have the greatest potential at the MW scale is the carbon lead acid battery. The negative electrode is made from carbon instead of lead, and according to the Economist article 'Lead-acid batteries. Recharged. A 150-year-old technology looks to the future' [The Economist, 2009], the carbon lead acid battery performed three times better than standard lead-acid batteries.

6.3.5 Advanced adiabatic compressed air energy storage (AA-CAES)

In the Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) system, surplus energy is used to compress air into a large underground storage space, as shown below diagrammatically in Figure 59.

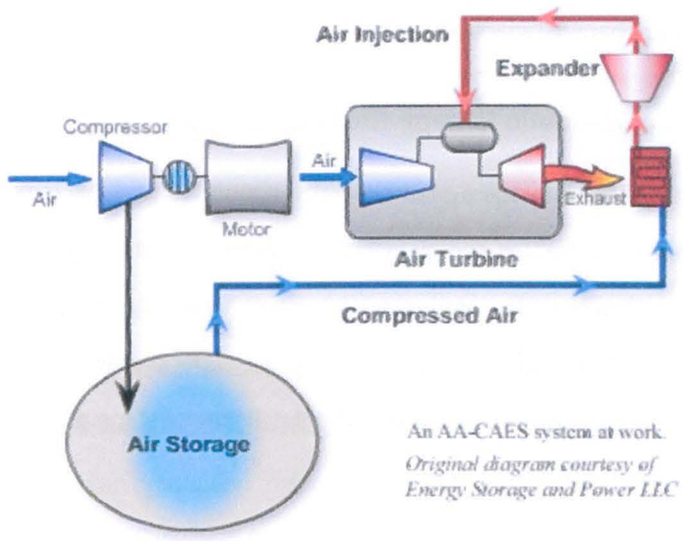

Figure 59: Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) system

When the energy is needed, the compressed air is expanded, and used to run power generation air turbines to generate electricity.

6.3.6 Flywheels

A flywheel is a rotating mechanical device that is used to store rotational energy. Flywheels have a significant moment of inertia, and so, resist changes in rotational speed. The amount of energy stored in a flywheel is proportional to the square of its rotational speed. Energy is transferred to a flywheel by applying torque to it using surplus power, thereby causing its rotational speed, and hence its stored energy, to increase. Conversely, a flywheel releases stored energy when required by applying torque to a mechanical load demand, which results in decreased rotational speed.

6.3.7 Ultra capacitors

An ultracapacitor, also known as an Electric Double Layer Capacitor (EDLC) or pseudocapacitor, is a high-energy version of a conventional electrolytic capacitor, but able to hold hundreds of times more energy, per unit volume or mass, than a conventional capacitor.

Although the ultracapacitor is an electrochemical device, there are no chemical reactions involved in its energy storage mechanism. Since the rate of charge and discharge is determined sorely by its physical properties, the ultracapacitor can release energy much faster, i.e. with more power, compared to a battery that relies on slower chemical reactions.

6.3.8 Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage systems (SMES) operate at very low temperatures, (around 4K), and store energy at times of surplus energy availability, in the field of a large magnetic coil with direct current (DC) flowing. This stored power is then converted back to AC electric current, when demanded. Low temperature SMES cooled by liquid helium, are commercially-available. High temperature SMES cooled by liquid nitrogen, is still in the development stage and may become a viable commercial energy storage source in the future.

SMES systems are large, and generally used for short duration applications, such as utility switching events, and are claimed to have efficiencies in excess of 95%.

6.4 Energy storage system selected

Of the options available, 'Projections of levelised cost benefit of grid-scale energy storage options' concluded that hydrogen fuel cells were the most viable option. This was based on projected incremental energy delivery costs at 7% discount rate for 2015 technology, which in turn was based on the expected improvements in efficiency as hydrogen-based technology strives for competitiveness in the transportation fuel market[43]. Based on these findings, it was decided that the captured energy in the RO plants would be best stored through the production of hydrogen.

It is noteworthy that the most viable option identified by 'Projections of levelised cost benefit of grid-scale energy storage options' was, what it referred to as, 'wind fuels', which involves using off-peak renewable energy to produce carbon neutral transport fuels [Doty and Shevgoor, 2009], by synthesis (or reaction) of:

- CO_2 produced by fossil fuel emissions, and
- Hydrogen produced by water electrolysis.

The objective of this research is to provide a stand-alone renewable energy installation that does not rely on conventional power, and so, this option, although judged to be the most attractive financially, was discounted.

6.5 Hydrogen production

All hydrogen production processes are based on the separation of hydrogen from hydrogen-containing feedstock. The separation method is dictated by the feedstock. The mainstream methods for production of hydrogen are shown below in Table 11, which was derived from the Hydrogen Production Overview Factsheet[44].

The reason for the use of hydrogen fuel cells within this research was to utilise captured energy. The systems that are available for the production of hydrogen using the energy produced by the renewable energy systems that is not used to produce desalinated water, are considered in terms of:

- Their feedstock
- Availability at each site, and
- Whether it involves the use of fossil fuels, as this research is focussed on not using fossil fuels
- The efficiency of using the captured energy to generate hydrogen.

Greater detail of these hydrogen production methods is available at 'Hydrogen production and storage R&D – Priorities and Gaps' [OECD/ IEA, 2006].

[43] The fuel cells within this study were assumed to have an efficiency of 70% for the conversion of hydrogen fuel to electricity.

[44] Fuel Cell and Hydrogen Energy Association Factsheet: Hydrogen production overview. Available at http://www.fchea.org/core/import/PDFs/factsheets/Hydrogen%20Production%20Overview_NEW.pdf [Last viewed on 7 August 2011].

Table 11: Methods of hydrogen production

Primary method	Process	Feedstock	Energy	Reasons not to employ method
Thermal	Steam Reformation	Natural gas	High temperature steam	Uses fossil fuel, and requires the conversion of captured energy to heat.
	Thermo-chemical water splitting	Water	High temperature heat from advanced gas-cooled nuclear reactors.	Requires the conversion of captured energy to heat.
	Gasification	Coal, Biomass	Steam and oxygen at high temperature and pressure.	Requires the conversion of captured energy to heat, and pressurized steam and oxygen.
	Pyrolysis	Biomass	Moderately high temperature steam	Requires the conversion of captured energy to heat.
Electrochemical	Electrolysis	Water	Electricity	None
	Photo-electro-chemical	Water	Direct sunlight	Does not use captured energy.
Biological	Photo-biological	Water and algae strains	Direct sunlight	Does not use captured energy.
	Anaerobic digestion	Biomass	High temperature heat	Requires the conversion of captured energy to heat.
	Fermentative microorganisms	Biomass	High temperature heat	Requires the conversion of captured energy to heat.

Based on the information above in Table 11, the only option that appears suitable for further consideration is the electrolysis of water using electricity, as all the other options:

- Use fossil fuels as the feedstock
- Require the inefficient conversion of the captured energy to heat/ pressure, or
- Do not use captured energy.

6.5.1 Electrolysis options

There are three main technologies available for electrolysis:

- Solid Oxide electrolysis
- Alkaline electrolysis, and
- Proton Exchange Membrane (PEM) electrolysis.

6.5.1.1 Solid Oxide electrolysis

The operation of a solid-oxide electrolyser depends on a solid ceramic electrolyte (zirconia/ ceria), which at temperatures of 800-1000°C transfers oxygen ions (O^{2-}). The solid oxide electrolyser requires a source of high-temperature heat. By operating at elevated temperatures, the heat input meets some of the energetic requirement for electrolysis and so, less electricity is required per m^3 of H_2 generated, compared with the other electrolyser technologies. However, to date, prototype solid-oxide electrolyser units have not achieved useful operational lives, and substantial engineering problems exist with respect to thermal cycling and gas sealing. As such, it is premature to make comparisons of these with alkaline and PEM electrolysers.

6.5.1.2 Alkaline electrolysis

An overview of the alkaline electrolysis process is shown below, based on the RoadstoHyCom website[45], in Figure 60.

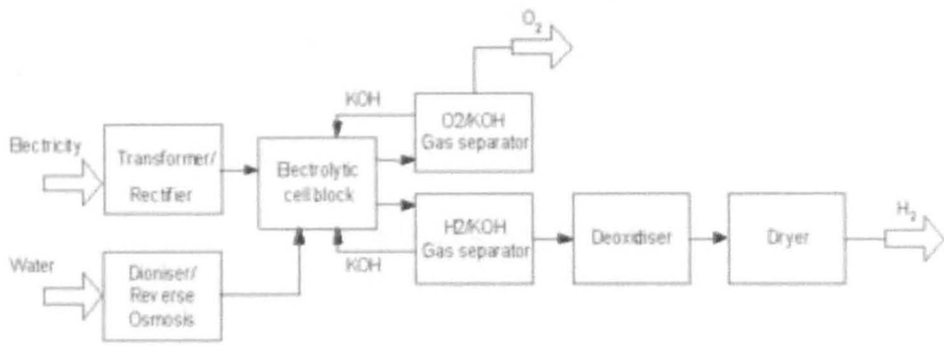

Figure 60: Alkaline electrolysis process

An alkaline electrolyser uses circulating electrolyte solution (usually potassium hydroxide, KOH) and, has conversion efficiencies in the range of 60-90%.

A modern alkaline electrolyser will achieve an efficiency of around 90% (consuming about 4kWh of electricity per m^3 of H_2), and deliver H_2 gas at up to 30bar, without auxiliary compression.

The key factors favouring the alkaline electrolyser are that:

- It does not need expensive platinum-based catalysts
- It is well-proven at large scale, and
- It is usually of lower unit cost than a PEM electrolyser.

6.5.1.3 Proton Exchange Membrane (PEM) electrolysis

An overview of the PEM electrolysis process is shown below[46] in Figure 61.

---

[45] Figure taken from 'RoadstoHyCom' onsite electrolysis webpage, available at http://www.ika.rwth-aachen.de/r2h/index.php/On-site_Electrolysis [Last viewed on 7 August 2011].

[46] Figure taken from article entitled 'Hydrogen refuelling stations are increasing as the number of hydrogen cars increase', available at http://www.onlinetes.com/tes-0710-electricity-produces-hydrogen-oxygen.aspx [Last viewed on 7 August 2011].

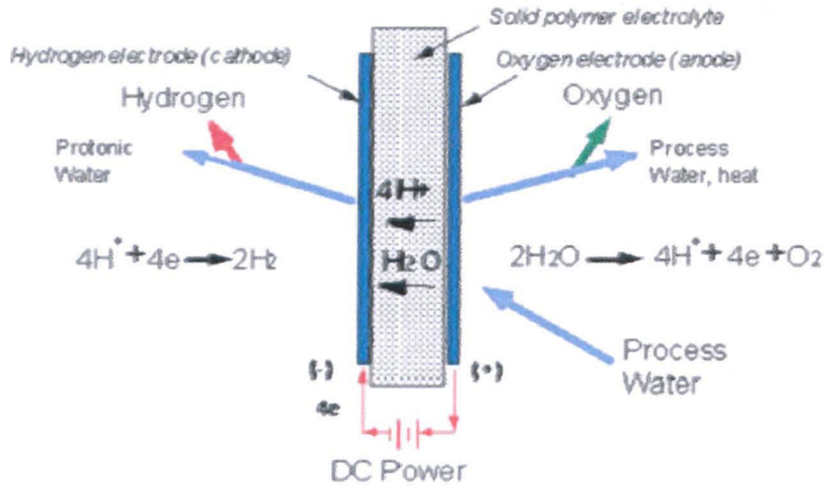

Figure 61: PEM electrolysis process

PEM electrolysers use precious metal catalysts (Platinum, Platinum/Ruthenium) and a solid polymeric electrolyte for transferring protons.

They have achieved more than 100,000 hours continuous operation without failure in critical environments[47]. They can operate at much higher current densities than alkaline electrolysers, and have conversion efficiencies ranging from 50-90%, but cannot yet achieve high efficiencies at high current densities.

Operation at high pressure (including high differential pressure between the hydrogen and oxygen side at up to 200bar) is proven, and the need for auxiliary gas compression is then considerably less than for an alkaline electrolyser.

The key factors favouring the PEM electrolyser are that:

- It avoids the requirement to circulate a liquid electrolyte
- It operates at a high current density (offering a small footprint), and
- It has the intrinsic ability to cope with transient variations in electrical power input (hence it has outstanding applications flexibility with respect to capturing intermittent renewable electricity supplies).

6.5.2 Conclusion

Based on the information available, the PEM electrolyser was selected for use in this research.

[47] An example being the provision of oxygen on nuclear submarines.

6.6 Storage of converted hydrogen

There are two basic mainstream hydrogen storage methodologies:

- Storage as a compressed gas, and
- Storage as a liquid

6.6.1 Storage as a compressed gas

The storage of gases in pressure vessels is a proven and tested technology, and many of the pumping systems employed for gas compression could be easily converted for hydrogen compression. The current norm is for hydrogen to be compressed to between 200 and 350bar, but storage pressures up to 700bar have been trialled [Hirscher, 2010].

6.6.2 Storage as a liquid

The storage of liquefied hydrogen is once again a tried and tested technology[48]. In comparison to compressed hydrogen, the density of the liquefied hydrogen is considerably higher, which is a distinct advantage in terms of space requirement, but the liquefied hydrogen requires complex and sophisticated storage devices with vacuum insulation and pressure regulation.

6.6.3 Conclusion

Due to the complexities associated with the management of liquefied hydrogen, compressed hydrogen gas at 300bar was considered for this research.

6.7 Power dispatch.

The device to be employed for power dispatch is the fuel cell. There are a variety of fuel cells available, with different advantages and disadvantages. These are concisely explained at the Fuel Cell Test and Evaluation Centre (FCTec) webpage[49]. For the purposes of this modelling exercise, the fuel cell needs to be able to:

- Start up quickly to dispatch power to keep the RO plant running, and
- Change power output rapidly, based on the varying demands of the RO plant.

---

[48] Hydrogen was first liquefied by J. Dewar in 1898.

[49] See http://www.fctec.com/fctec_types.asp [Last viewed on 7 August 2011].

On the basis of these criteria, the Proton Exchange Membrane (PEM) fuel cell was selected[50] to be modelled.

6.7.1 The PEM Fuel Cell

The method of operation of the PEM fuel cell is illustrated below in Figure 62, and briefly explained in the following text.

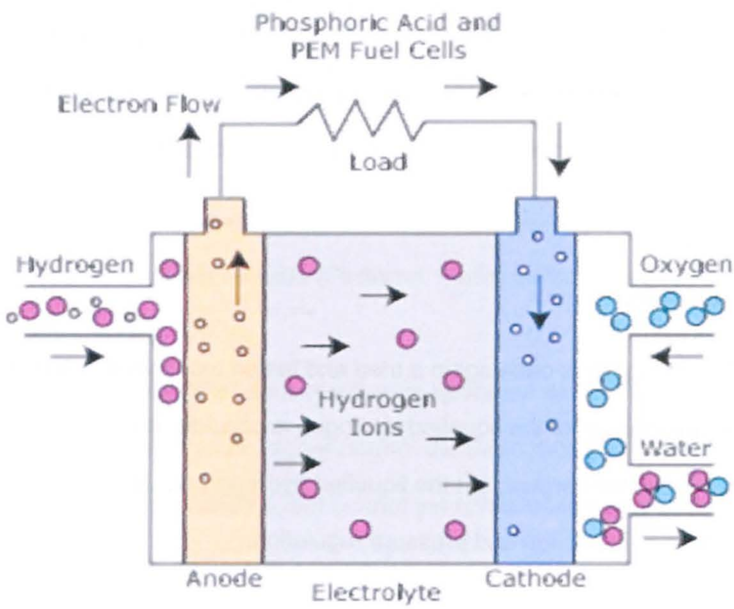

Figure 62: PEM Fuel Cell Operation

The PEM fuel cell uses a solid polymer membrane as the electrolyte. This polymer is permeable to protons when it is saturated with water, but it does not conduct electrons.

The fuel for the PEM fuel cell is hydrogen, and the charge carrier is the hydrogen ion (proton). At the anode, the hydrogen molecule is split into hydrogen ions (protons) and electrons. The hydrogen ions permeate across the electrolyte to the cathode while the electrons flow through an external circuit and produce electric power. Oxygen, in the form of air, is supplied to the cathode, and combines with the electrons and the hydrogen ions to produce water. The reactions at the electrodes are shown below in Table 12.

Table 12: PEM Fuel Cell electrode reactions

Reactions	Chemical formulae
Anode Reactions	$2H_2 \Rightarrow 4H^+ + 4_e$
Cathode Reactions	$O_2 + 4H^+ + 4_e \Rightarrow 2\,H_2O$
Overall Cell Reactions	$2H_2 + O_2 \Rightarrow 2\,H_2O$

[50] It is noteworthy that although the PEM fuel cell is the best technically suited to the demands of the scenarios being modelled, the electrolyte is required to be saturated with water to operate optimally. Careful control of the moisture of the anode and cathode streams is important to avoid either flooding or drying out. Both of these events can be destructive for the PEM fuel cell stack.

PEM fuel cells work as separate cells, and are combined, into stacks to deliver the required power levels.

6.8 Efficiency of process

Table 13 below shows the efficiency of the different stages of selected process.

Table 13: Efficiency of energy storage and re-use

Process	Conversion to hydrogen	Power Storage	Power dispatch	Synchronisation[51]
Method employed	PEM Electrolysis	Compressed Gas	Fuel cell	DC - AC
Efficiency (%)	75	85	50	90

6.8.1 Overall efficiency of energy storage and reuse process

The normal case (using conversion and storage as a gas) gives a 22.95% efficiency.

For the purpose of this research, a figure of 22% was adopted, which included a further reduction of 0.95% to take account of any other losses, such as evaporation.

6.8.2 Energy storage and re-use methodology

The logic illustrated below in Figure 63 was employed to model the energy being captured and reapplied, to enhance the productivity of the RO plant.

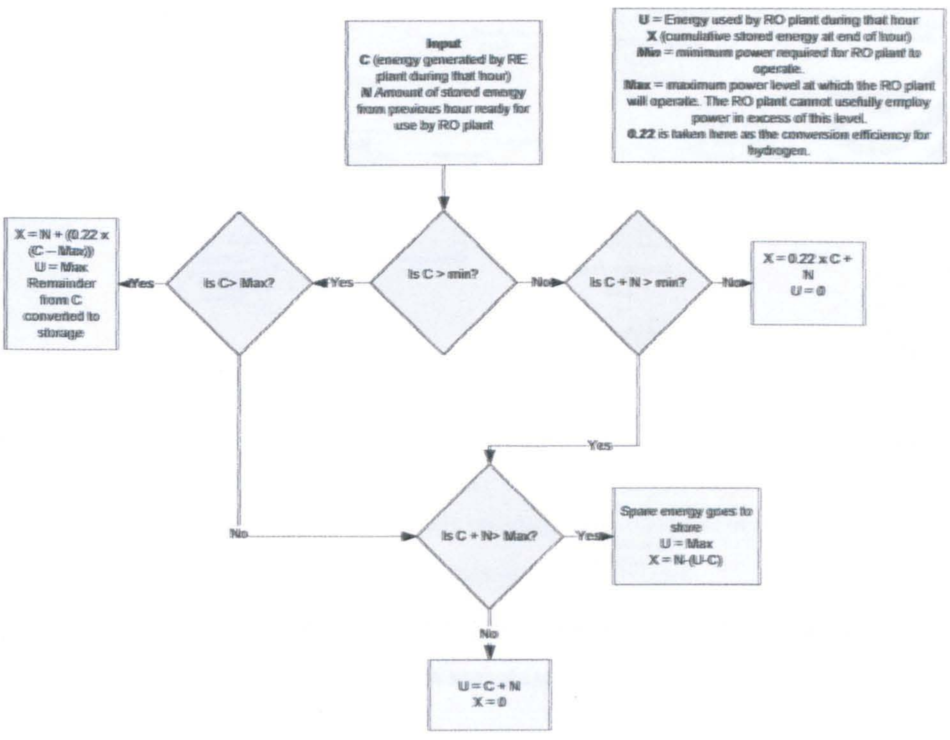

Figure 63: Logic applied to use captured energy to maintain maximum flowrate where possible

---

[51] Personal e-mail communication from Andy Barton, Technician managing synchronisation at West Beacon Farm. Details of West Beacon Farm are available at http://www.beaconenergy.co.uk/ [Last viewed on 7 August 2011].

6.8.3 Scenarios where the logic was applied

The scenarios that employed the reapplication of stored energy are illustrated below in Figure 64 and Figure 66 for Massawa, and Figure 65 and Figure 67 for Newhaven, respectively.

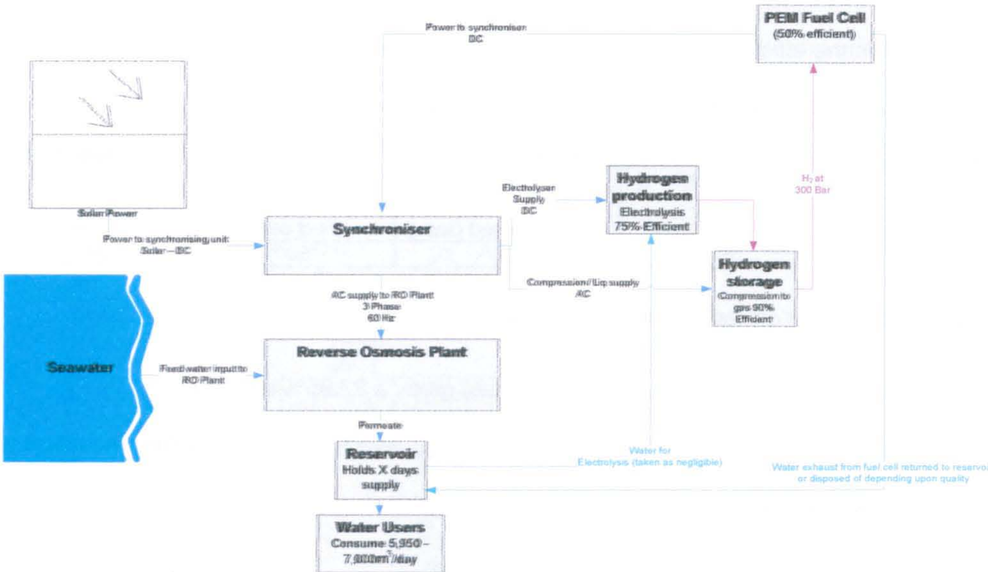

Figure 64: Massawa solar scenario for utilisation of captured energy to run RO plant using hydrogen storage and reuse

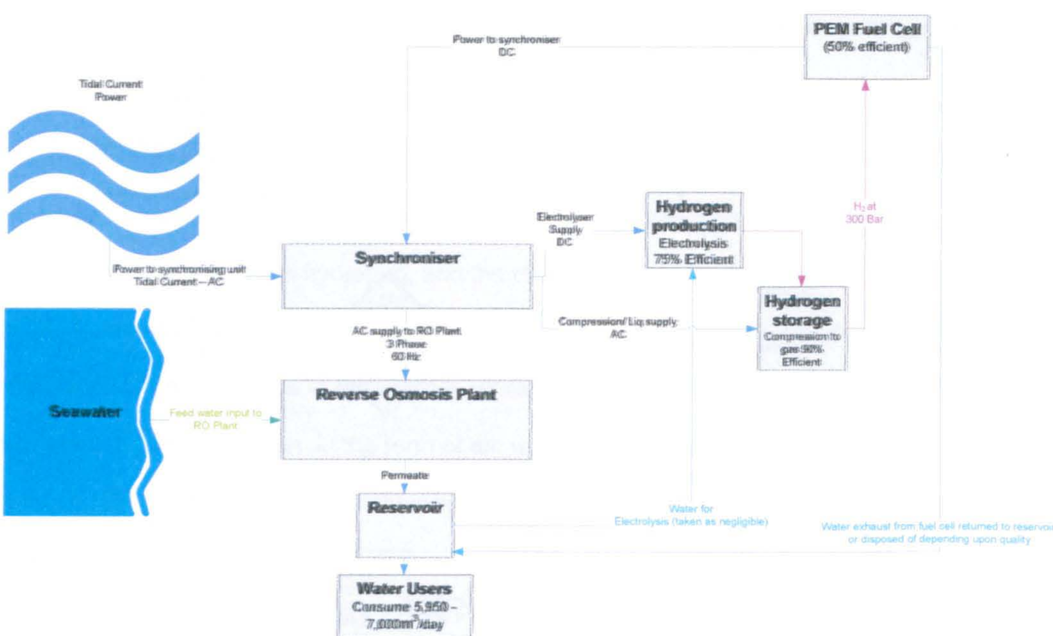

Figure 65: Newhaven Tidal Current scenario for utilisation of captured energy to run RO plant using hydrogen storage and reuse

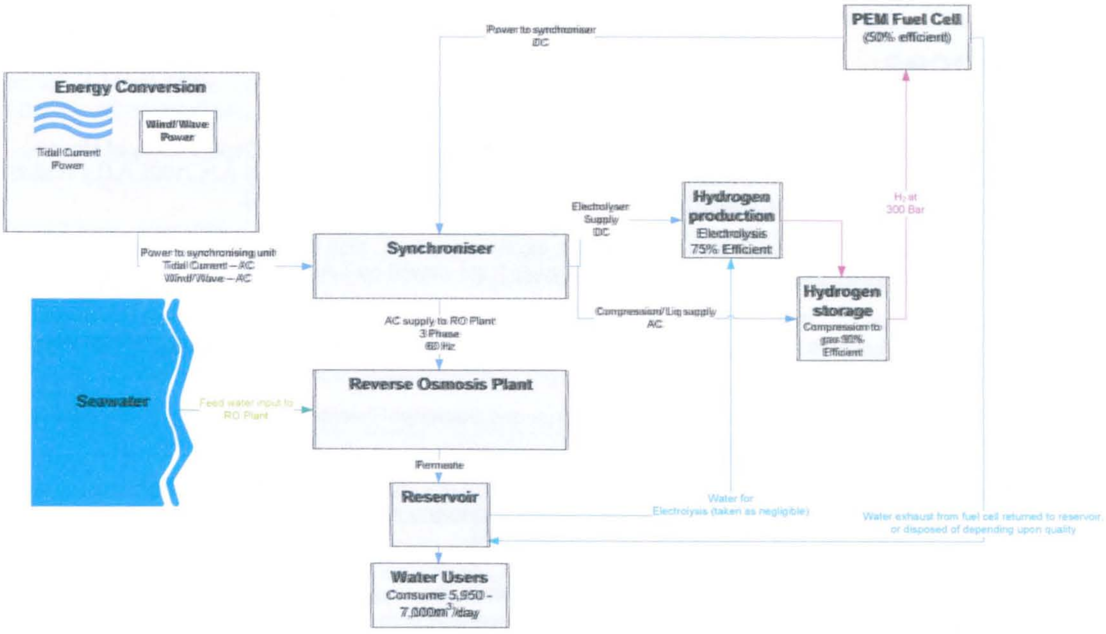

Figure 66: Massawa solar with wind/ wave scenarios for utilisation of captured energy to run RO plant using hydrogen storage and reuse

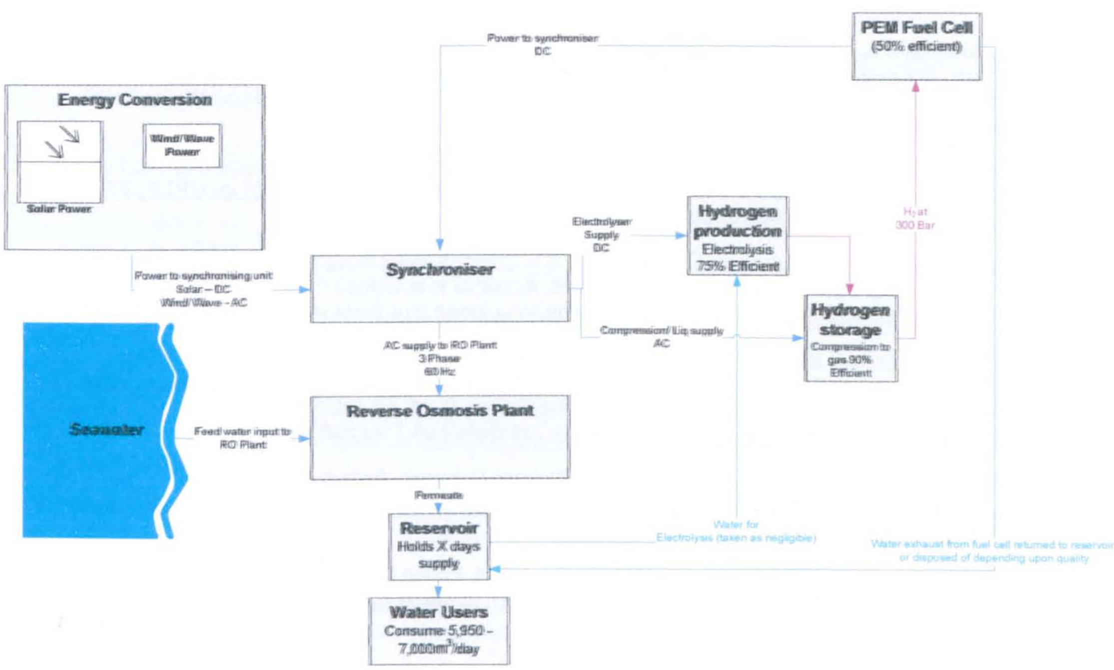

Figure 67: Newhaven Tidal Current with wind/ wave scenarios for utilisation of captured energy to run RO plant using hydrogen storage and reuse

7 References

Abdelrahman S. M. 1995. Statistical Wave Parameters Offshore Jeddah Coast. Marine Physics Dept., Faculty of Marine Science King Abdulaziz University, Jeddah, Saudi Arabia JKAU: Mar. Sci., vol. 6, pp. 25-37 (1415 A.H. /1995 A.D.) available at http://www.kau.edu.sa/Files/320/Researches/51883_22015.pdf [Last viewed on 7 August 2011].

Alberti F. Mosto N. Sommariva C. 2008. 'Salt production for zero discharge system'. Mott MacDonald, UAE. Available at http://www.desalination.biz/news/magazine_article.asp?id=4783&title [Last viewed on 7 August 2011].

Al-Karaghouli A. A., Kazmerski L. L. 'Renewable Energy Opportunities in Water Desalination' by the National Renewable Energy Laboratory (NREL). Available at http://wrri.nmsu.edu/conf/conf11/renewable_energy_water_desal.pdf [Last viewed on 1 April 2012].

Andrews, W. T., Shumway S. A., Russell B. 'Design of a 10,000 cu-m/d Seawater Reverse Osmosis Plant on Providence Island, The Bahamas.'. Available at http://www.waterfields.bm/

CEFAS. 2011. Station 20: Eastbourne. Available at http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/sea-temperature-and-salinity-trends/presentation-of-results/station-20-eastbourne.aspx?RedirectMessage=true [Last viewed on 7 August 2011].

Defra (Defra Market Transformation Programme). March 2008 'BNWAT27: Domestic external water use: An overview'. Version 1.0. Marketing Transformation Programme. 25 March 2008. available from http://www.google.co.uk/url?sa=t&rct=j&q=wrc%2C%202005%2C%20increasing%20the%20value%20of%20domestic%20water%20use%20data%20for%20demand%20management&source=web&cd=2&ved=0CCcQFjAB&url=http%3A%2F%2Fefficient-products.defra.gov.uk%2Fspm%2Fdownload%2Fdocument%2Fid%2F930&ei=mDCpTqXJIoGl8gPAoo3sCw&usg=AFQjCNG64wkze9kCxHCiTAd3Scrpyj7jBg [Last viewed on 7 August 2011].

Doty G. N., David L. McCree D. L., and Doty F. D. 2010. 'Projections of levelised cost benefit of grid-scale energy storage options', of Doty Energy, Columbia, SC USA. Proceedings of Energy Sustainability 2010 May 17-22, 2010, Phoenix, Arizona. USA. Available at http://www.dotyenergy.com/PDFs/Doty-90377-Storage-ASME-ES10.pdf [Last viewed on 7 August 2011].

Doty F. D., Shevgoor S. 2009. "Securing our Transportation Future by Using Off-Peak Wind to Recycle CO_2 into Fuels", ES2009- 90182, ASME Joint Conferences, San Francisco, 2009. Available at http://www.dotyenergy.com/PDFs/ES09-Doty-1-windfuels-90182.pdf [Last viewed on 7 August 2011].

Dow (Dow Industries). ROSA 6.2 (now superseded by version 727) is Dow Industries Reverse Osmosis Design Programme which allows their membranes to be modelled in a variety of states. Available to download from http://www.dowwaterandprocess.com/support_training/design_tools/rosa_down.htm [Last viewed on 7 August 2011].

Environmental Change Institute. July 2005. 'Variability of UK marine resources - An assessment of the variability characteristics of the UK's wave and tidal current power resources and their implications for large scale development scenarios'. Produced by the Environmental Change Institute, for the Carbon Trust: Available at https://www.oreg.ca/docs/Variabilityofwaveandtidalstream[1].pdf . [Last viewed on 7 August 2011].

Folley M. 2007 'A Wave Powered desalination Plant' poster from Queens University Belfast available at http://www.qub.ac.uk/research-centres/WelcometoSustainableDevelopmentatQueens/filestore/Filetoupload,129153,en.pdf [Last viewed on 1 April 2012].

Ghermandi A., Messalem R. July 2009. Desalination and Water Treatment. Pages 285–296, Solar-driven desalination with reverse osmosis: the state of the art. Ben-Gurion University of the Negev, Zuckerberg Institute for Water Research, Desalination & Water Treatment, Beer Sheva, Israel available at http://web2.bgu.ac.il/ziwr/faculty/messalem/documents/1.pdf

Gijs A.M. van Kuik. February 2007. 'The Lanchester–Betz–Joukowsky limit.' Published in 'Wind Energy Magazine' 14 February 2007. Available at http://onlinelibrary.wiley.com/doi/10.1002/we.218/abstract [Last viewed on 7 August 2011].

Green M. A., Emery K., Hishikawa Y., Warta W. 2009. 'Solar Cell Efficiency Tables (Version 33)'. Progress in Photovoltaics: Research and Applications Volume 17, Issue 1. Pages 85–94. Available at http://159.226.64.60/fckeditor/UserFiles/File/tyndc/reference/19909584825552.pdf [Last viewed on 7 August 2011].

Green Transport and Energy. March 2009. 'High speed monorails instead of high speed trains'. Green Transport and Energy Blog. Available at http://greentransportandenergy.blogspot.com/2009/03/high-speed-suspended-monorails-instead.html [Last viewed on 7 August 2011].

Hardisity J. 2009. 'The Analysis of Tidal Stream Power'. ISBN: 978-0-470-72451-4. The full text is available at http://books.google.co.uk/books?id=SFUztwHVyHgC&printsec=frontcover&dq=The+Analysis+of+Tidal+Stream+Power.+by+Jack+Hardisty&source=bl&ots=pYpF5RdIzA&sig=qcvnE71O4ErSgyhsPlh70AEaUvo&hl=en&ei=pMqtTK6BOcq6jAfJsL1y&sa=X&oi=book_result&ct=result&resnum=2&ved=0CB8Q6AEwAQ#v=onepage&q&f=false [Last viewed on 7 August 2011].

Hirscher M. 2010. 'Handbook of Hydrogen Storage' Published by WILEY-VCH Verlag GmBh & Co. KGaA, Weinheim. 2010. ISBM: 978-3-527-32273-2.

Lachish U. March 2003. 'Optimizing the Efficiency of Reverse Osmosis Seawater Desalination'. Available at http://urila.tripod.com/Seawater.htm [Last viewed on 7 August 2011].

LaMonica M. May 2010. 'Wave-powered desalination pump permitted in Gulf', available at http://news.cnet.com/8301-11128_3-20006269-54.html [Last viewed on 1 April 2012].

Manolakos D., Papadakis G., Kyritsis S. and Bouzianas K. 'Experimental evaluation of an autonomous low-temperature solar Rankine cycle system for reverse osmosis desalination' by Agricultural University of Athens, Department of Agricultural Engineering published in Desalination 203 (2007) Page 366–374 available at http://www.desline.com/articoli/8050.pdf [Last viewed on 1 April 2012].

Marques de Carvalho P. Riffel D. B., Freire C and Montenegro F. F. D. 2004. Progress in Photovoltaics: Research and Applications. 2004; 12:373–385 (DOI: 10.1002/pip.543). The Brazilian Experience with a Photovoltaic Powered Reverse Osmosis. Available at http://onlinelibrary.wiley.com/store/10.1002/pip.543/asset/543_ftp.pdf;jsessionid=155F63049F8CC93AB18DCFFE64D68B0F.d01t01?v=1&t=h6diffne&s=4dd80d342551e53b272d17210467f37fe5d2f981 [Last viewed on 7 August 2011].

Mitchell S. B., Pope D. J. 2004. 'Prediction of nearshore wave energy distribution by analysis of numerical wave model output, East Sussex coastline, UK.' Page 101. University of Brighton. Published in Geological Society, London, Engineering Geology Special Publications; 2004; v. 20; p. 99-107 which is available at ;http://books.google.com/books?hl=en&lr=&id=Vm0UasbPFXQC&oi=fnd&pg=PA99&ots=3zTd5Yiqu_&sig=eKumG3EHKbCdaSb918kVtB8bacQ#v=onepage&q&f=false [Last viewed on 7 August 2011].

MTMC (Marine and Technical Marketing Consultants). May 2007.Atlas of Tidal Energy Resource on the South East Coast of England, prepared for the South East England Development Agency (SEEDA). Available at http://www.solentoceanenergy.com/Seeda_final5.pdf [Last viewed on 7 August 2011].

National Oceanographic Centre. 2011. The National Oceanographic Centre – National Environmental Research Council webpage at http://www.pol.ac.uk/ntslf/data.html [Last viewed on 7 August 2011].

OECD/ IEA (Organisation for Economic Cooperation and Development/ International Energy Agency). 2006. Hydrogen production and storage. R&D – Priorities and Gaps'. Hydrogen Co-ordination Group. Available at http://www.iea.org/papers/2006/hydrogen.pdf [Last viewed on 7 August 2011].

OECD/IEA. 2009. Annex 2 'Prospects for Large-Scale Energy Storage in Decarbonised Power Grids'. Working Paper. Available at http://www.iea.org/papers/2009/energy_storage.pdf [Last viewed on 7 August 2011].

Olga L., Sallangos V. July 2004. 'Operating experience of the Dhekelia seawater desalination plant using an innovative energy recovery system' Desalination 173 (2005) pages 91–102 Available at http://159.226.64.60/fckeditor/UserFiles/File/tyndc/reference/19909584825552.pdf [Last viewed on 7 August 2011].

Rheinlander J. 2007 De-central Water and Power Supply Integrating Reneweable Energy – Technical and Economic Performance Prediction. Center for Solar Energy and Hydrogen Research Baden-Wurttemberg, Germany. Published by Springer. Available at http://books.google.co.uk/books?id=iA75bZKcilYC&pg=PA348&lpg=PA348&dq=intermittent+operation+of+ro+plant&source=bl&ots=CK_s-CRvyO&sig=gDp5Pilzgr8CXXNUVBu0ClbPJ2o&hl=en&sa=X&ei=wRCLT-DBKTC0QWzxcW5CQ&ved=0CFgQ6AEwBA#v=onepage&q=intermittent%20operation%20of%20ro%20plant&f=false [Last viewed on 7 August 2011].

SETIS (European Union Strategic Energy Technologies Information System). 2011. '2011 Update of the Technology Map for the SET-Plan'. Available at http://setis.ec.europa.eu/newsroom-items-folder/concentrated-solar-power-generation [Last viewed on 1 April 2012].

Solar Facts and Advice. 2010. 'Cadmium Telluride – The Good and the Bad'. Solar Facts and Advice website. Available at http://www.solar-facts-and-advice.com/cadmium-telluride.html [Last viewed on 7 August 2011].

Swiss Metal Assets. 2010. 'Thin-film PV comes one step closer to rivalling crystalline PV in efficiency'. Available at http://www.swissmetalassets.com/thin-film-pv-step-closer-rivaling.html#page=page-1 [Last viewed on 7 August 2011].

The Economist. Jan 2009. Lead-acid batteries. Recharged. A 150-year-old technology looks to the future. Available at http://www.economist.com/node/12924031 [Last viewed on 7 August 2011].

Thomson A. M. June 2003. 'Reverse-Osmosis Desalination of Seawater Powered by Photovoltaics without Batteries', Doctoral Thesis Page 95 Loughborough University. Available at http://www-staff.lboro.ac.uk/~elmt/Murray%20Thomson%20Thesis.pdf [Last viewed on 7 August 2011].

a) Massawa Seawater temperatures taken from pages 110 and 111.
b) Average monthly irradiance taken from page 95.

Thomson M., Miranda M., Gwillim J., Rowbottom A., Draisey I. 2001. 'Batteryless Reverse Osmosis Desalination System'. ETSU S/P2/00305/REP. DTI/Pub URN 01/1121. Chemical analysis of pre-treated feedwater taken from Appendix C of Report. Available at http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file16527.pdf [Last viewed on 7 August 2011].

Trabish H. K. 2012. 'CSP and PV Solar Make Each Other More Valuable'. Available at http://www.greentechmedia.com/articles/read/CSP-and-PV-Solar-Make-Each-Other-More-Valuable/ [Last viewed 1 June 2012].

US DoE (US Department of Energy). May 2007. 'Pumping systems Tip Sheet 2. Control strategies for centrifugal pumps with variable flowrate requirements' DOE/GO-102007-2230, available at http://www1.eere.energy.gov/industry/bestpractices/pdfs/38949.pdf [Last viewed on 7 August 2011].

USDoE (US Department of Energy). 2012. Water Power Program. 'Marine and Hydrokinetics Technology Listing'. Available at http://www1.eere.energy.gov/water/hydrokinetic/listings.aspx?type=Tech [Last viewed 1 September 2012].

World Health Organization (WHO). 2011 Guidelines for drinking-water quality –4th Ed ISBN 978 92 4 154815 1 . Available at http://www.who.int/water_sanitation_health/publications/2011/dwq_chapters/en/index.html [Last viewed on 7 August 2011].

Appendix C

This Appendix discusses the water required for the hydrogen fuel cycle modelled as part of this research.

1. Electrolysis water consumption

The 'Summary of Electrolytic Hydrogen Production Milestone Completion Report' [Ivy, 2004] presents a summary of analysis of various electrolysers that are currently available. The electrolysis process outputs for each of the options considered are shown below in Table 1.

Table 1: Water inputs and hydrogen and water outputs from various electrolysers

	Water input (kg/hr)	Hydrogen output (kg/hr)	Oxygen output (kg/hr)	Water removal (kg/hr)	Hydrogen per input water (% mass)	Water reclaimed (% mass)
Option 1	60	5.4	43	11.8	**9**	**20**
Option 2	42	3.77	30.01	8.21	**9**	**20**
Option 3	8.4	0.9	7.1	0.4	**11**	**5**
Option 4	485	43.59	346.51	94.82	**9**	**20**
Option 5	4.5	0.45	3.57	0.48	**10**	**11**

For the purposes of this research, based on Table 1 above, the:

- Hydrogen produced from 1kg of water was taken as 0.1kg (10%), and
- The water reclaimed from the electrolyser from 1kg of water was 0.2kg (20%).

2. Fuel cell exhaust

Fuel cells operate based on the chemical reaction: $2H_2 + O_2 = 2H_2O$. The stoichiometry of this chemical reaction indicates that for every mole of hydrogen (2.1 g) consumed by the fuel cell, one mole of water is expelled (18.2g).

Therefore, in theory, (by mass), approximately 8.66 times the mass of water is available to be reclaimed for each unit of hydrogen consumed by the fuel cell.

According to 'Comparative Studies of Polymer Electrolyte Membrane Fuel Cell Stacks and Single Cells' [Chu and Jiang, 2000], around 66% of this expelled water can be collected, and this recovery rate could be improved by using a condenser at the cathode exhaust, to minimise the evaporation losses [Dhanasekaran, 2007].

For the purposes of this research, the water recovered from each kg of hydrogen consumed by the fuel cell will be 5.7 litre (based on the density of water being 1 kg/litre, and a collection efficiency of 66%).

The water consumption and its return for the hydrogen fuel system modelled, are shown below in Figure 1.

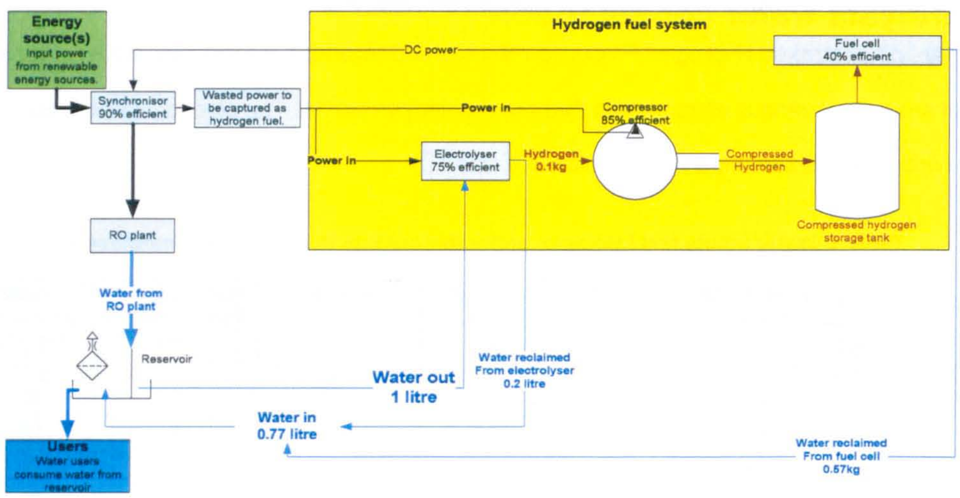

Figure 1: Hydrogen fuel cycle

3. Hydrogen consumed by fuel cell

For the purposes of this research, hydrogen consumed by the fuel cell is simply a function of the power demanded by the RO plant, to maintain full flow.

The energy available in 1 kg of compressed hydrogen is taken as 143 MJ. The efficiency of use of this hydrogen, is taken as:

$$H_{2\eta}=C_{\eta} \times FC_{\eta} \times Sy_{\eta}$$

where:

$H_{2\eta}$ - the efficiency of hydrogen use

C_{η}- the efficiency of hydrogen compression to a gas – taken as 85%

FC_{η} - the efficiency of hydrogen conversion to DC electricity within the fuel cell– taken as 40%

Sy_{η} - the efficiency of electric power conversion from DC to AC, for use by RO plant– taken as 90%

Therefore, 30.6% (43.8 MJ) of the power available in each kg of hydrogen, is available for use by the RO plant, which equates to approximately 12 kWh/kg of hydrogen.

Taking the most successful scenarios that employed hydrogen fuel at Massawa and Newhaven, it can be seen from Table 2 below, that the water lost due to the hydrogen fuel cycle, is relatively insignificant over the course of the year, at 0.002% and 0.0015% for Massawa and Newhaven, respectively.

Table 2: Water lost due to hydrogen fuel cycle

	Power dispatched ($kWx10^6$)	Mass of hydrogen fuel used (kg)	Volume of water input required (m^3)	Volume of water lost during year (m^3)	Percentage of annual water production lost due to hydrogen fuel cycle (%)
Massawa	0.68	56636	226.5	52.10	**0.0020**
Newhaven	0.49	41044	164.2	37.76	**0.00147**

References

Chu D., Jiang R. February 2000. 'Comparative Studies of Polymer Electrolyte Membrane Fuel Cell Stacks and Single Cells'. Army Research Laboratory. ARL-TR-2087. Available at http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA375122&Location=U2&doc=GetTRDoc.pdf [Last viewed on 7 August 2011].

Dhanasekaran B. December 2007. 'A New Water Source: Can Fuel Cells Provide Safe Potable Water Sources?' Masters Degree Thesis. Arizona State University. Available at http://enpub.fulton.asu.edu/pwest/Theses_Diss/New_Folder/Brindha%20Thesis.pdf [Last viewed on 7 August 2011].

Ivy J. September 2004.The 'Summary of Electrolytic Hydrogen Production Milestone Completion Report'. September 2004 • NREL/MP-560-36734. National Renewable Energy Laboratory (NREL). Available at http://www.nrel.gov/hydrogen/pdfs/36734.pdf [Last viewed on 7 August 2011].